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DESIGN, FABRICATION AND TESTING OF AN ELECTRO - RHEOLOGICAL FLUID DAMPER

by
Lt. ISHAN TANDON

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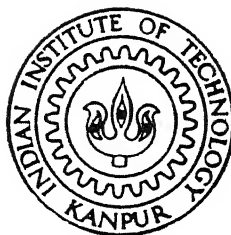
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DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

FEBRUARY 1997

**DESIGN, FABRICATION AND TESTING
OF AN
ELECTRO-RHEOLOGICAL FLUID DAMPER**

A Thesis submitted
in partial fulfilment of the requirements
for the Degree of
Master of Technology

by
Lt. Ishan Tandon

to the

**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY**

Feb, 1997

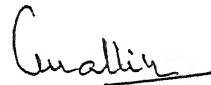
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CERTIFICATE

Certified that the work contained in this thesis, entitled "**DESIGN, FABRICATION AND TESTING OF AN ELECTRO-RHEOLOGICAL FLUID DAMPER**" has been carried out by **Lt. Ishan Tandon** under my supervision and that the same has not been submitted elsewhere for a degree.



Dr. A. K. MALLIK

Professor

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Feb, 1997

*Dedicated to my wife
and son.*

ACKNOWLEDGEMENT

I am indeed highly indebted to my guide and Supervisor Dr A K Mallik for his unique insight and invaluable guidance. I owe my Thesis to him for his motivation, constant encouragement and moral support, especially in trying times during my experimentation. I am extremely thankful to him for introducing me to this new field of smart fluids and the critical appreciation of the thesis.

I would also like to thank Dr. Gupta Bhaya for his invaluable advice and insight, during the preparation of the fluid. I would also like to thank Mr. Vishal Saxena for his invaluable advice for the electrical appreciation of the fluid. I would like to express my gratitude to Dr. Satyendra Kumar for sparing the High Voltage DC Supply Unit, which was vital for the experimentation.

I also take this opportunity to thank Mr. Vishwakarma for helping me in designing the damper. I am extremely grateful to Mr. Kuldeep Vishwakarma for his whole hearted interest in the fabrication and the design aspects of the model. It is due to his keen interest and skill that the fabrication of the efficient and effective damper was possible. The preparation of the fluid would indeed not have been possible without the support of Mr. Ajay Garg (Ph.D), who was always there to extend his help. I would also like to thank Mr P M Jha for his advice on the fabrication of the Model.

I have no words to express my gratitude to Mr A C Trivedi for his selfless help in the preparation of my Thesis without whom it would not have been possible to complete the thesis in time. I would also like to thank Mr. M M Singh for his indispensable support during experimentation.

I would like to thank all my friends at IIT, Kanpur who have made my stay here comfortable and invaluable. I specially thank Atul and Vikas for helping me with the computers and making my stay memorable. Finally, I would like to thank Lt. S K Srivastava for being an excellent moral support and a great help at all times.

Lt. ISHAN TANDON

ABSTRACT

In Passive vibration dampers, high damping is required to safeguard the machinery from failures in the resonance zone. But, this leads to a compromise on the transmissibility and the isolation in the high frequency operating zone. The high damping factor causes the isolation, of the foundation from a running machinery or a vibrating mass from the base vibrations, to reduce increasing the transmissibility to near unity.

The compromise is overcome by vibration dampers, using variable damping elements. One such variable damping element is the "Electro-Rheological Fluid". The property of this fluid is that the rheology (here viscosity) of the fluid is modified on the application of electric fields.

The thesis deals with this variable element, and the feasibility of using it in vibration damping. A model of a conventional (cylinder-piston assembly) vibration damper was designed and fabricated on the basis of published papers by different authors, and tested the feasibility of using these fluids as vibration damping elements. Two kinds of fluids were prepared using silica and starch as the different dispersed phases. Experiments were conducted using these fluids by mounting the model on a shaker, providing harmonic base excitation. The transmissibility curves were obtained with the variation in voltages to analyse the damping characteristics on the application of electric fields. DC as well as AC fields were used to quantify the effects. Certain parameters such as electric field intensity, concentration of the dispersed phase, shear velocity and the effects of the different constituents of the fluid, on the damping characteristics are reported.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Vibrations are a part of life and in practice do cause a lot of unavoidable problems, even leading to catastrophic failures. Thus, it has been every engineers and designers nightmare and endeavor to either isolate these vibrations or to suitably reduce them. Delicate instruments are isolated from shock and unnecessary vibrations by fitting vibration isolators such as cork, rubber etc. or even vibration dampers, which are generally passive elements . These are springs, viscous dampers or a combination of both.

The extent of vibration being transmitted to a rigidly attached equipment from any vibrating source gives the measure of how well or badly the system is actually isolated and this is often measured by an inverse index called "TRANSMISSIBILITY" (TR). Transmissibility is defined as the ratio of the

amplitude of the vibrating equipment ,y, to the amplitude of the vibrating source ,x.

A vibration isolater system can be modelled as a conventional spring-mass-damper system as shown in Fig 1.1. For such a system, the harmonic transmissibility is given by

$$TR = \left| \frac{y}{x} \right| = \sqrt{\left(\frac{1 + (2\xi r)^2}{(1-r^2)^2 + (2\xi r)^2} \right)}$$

where,

k=stiffness

c=damping constant (viscous)

m=mass

ω =forcing frequency

$r = \omega / \omega_n$

ω_n =natural frequency = $\sqrt{k/m}$, and

ξ =damping ratio = $c / \sqrt{2km}$

The results obtained from the above expression are shown graphically in Fig. 1.2.

It is obvious that one needs to consider basically three different frequency regimes: (i) the region where $\omega < \omega_n$, (ii) the region around $\omega = \omega_n$ (iii) the region where $\omega > \sqrt{2} \omega_n$. In the first region, the damping has negligible influence on TR, whereas in the third region higher damping is detrimental for isolation. It is only in the second region the damping controls the transmissibility very effectively. Furthermore, a good isolator should provide low ω_n so that $\omega / \omega_n \gg \sqrt{2}$ in the operating range to ensure $TR < 1$. But if the system is subjected to a shock or a broad band excitation, then there is a high probability that the forcing frequencies will encompass the resonance frequency of the system. Consequently the TR will be heavily dependent on the damping and the system should have high damping.

Thus always a compromise is made between the damping and the TR, as for shock control a high damping is required but for vibration control (isolation)

the damping required is low. In the case of a running machinery, when the machine is started it has to pass through the resonance region, even if for a very small period of time. If the system is not damped effectively, this

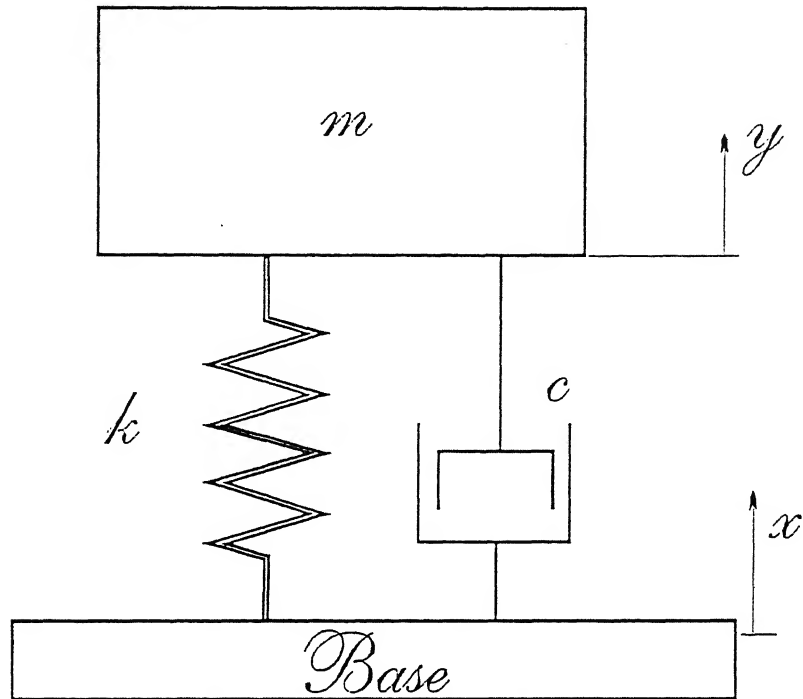
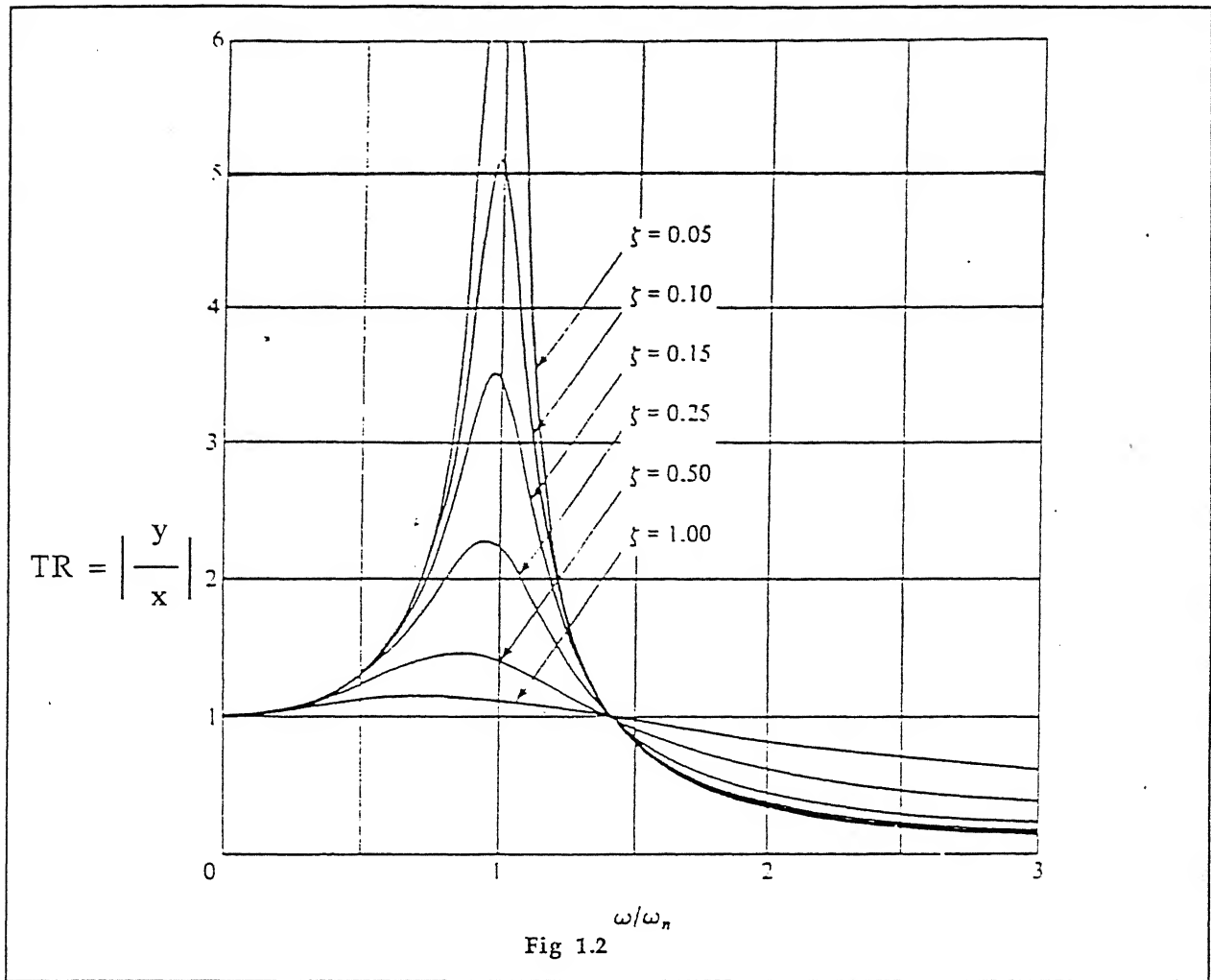


Fig 1.1

may lead to failure of the machine, thus requiring a high damping to cross the resonance. But, on the other hand at high operating speeds, a very low damping is required. To safe-guard the machinery from failure and also for its effective running, a compromise is made, as this is the most optimum and the best way to passively damp the system.

This dilemma of compromise gave birth to semi-active control vibration dampers, whose damping characteristics one can control, as per the requirement. This in turn made brains tick for variable damping elements. One promising method to achieve this is to use ELECTRO-RHEOLOGICAL FLUIDS [8]. Using such a fluid for a variable damping element, the semi-active dampers are designed to overcome the dilemma faced while designing a passive damper, whose viscosity can not be controlled and remains a constant parameter.



The major goal of the present thesis is to design a semi-active control vibration damper (conventional piston -cylinder assembly) on the basis of the electro-rheological effects as reported and discussed by different authors in their works published in various Journals and Patents. Also ,the damper is put to test on a shaker for analysing the transmissibility and the damping characteristics under controlled conditions.

1.2 Literature Survey

The variable damping element(Electro-Rheological Fluid) has been tested for the damping effects and is also being introduced commercially . Many authors have reported the effects for these ER fluids being used for semi-active control vibration dampers [8,13] . The authors used prototype dampers to determine the viscous and the coulomb friction terms with the digital processing of the experimental records. Starch- Silicon oil suspensions have

been used to attain the state of critical damping , using the prototype model of a conventional dashpot assembly . Most of the authors have used this fluid in the shearing model [13] using rotory dampers and shown promising effects for torsional damping.

The ER clutch, also first patented by Winslow [1], has been the stepping stone for the semi-active control clutches in the automotive industry. Apart from the clutches, variable engine mounts, engine dampers, etc. are already in the final stages. The ER vibration damper is summarised explicitly in reference [11].

1.3 Objective and Scope of Work

The primary objective of this thesis is the testing and analysis of an Electro-Rheological fluid vibration damper.

In the first step a viable model of a dashpot-piston damper was designed and fabricated on the basis of the requirement and safety as per the guidelines in reference [8].

The second step was to make an electro- rheological fluid on the basis of the literature survey, and the findings of various authors. Patents of these fluids were also referred to. The ER fluid was prepared keeping in mind the many constraints and the effect of the constituents on the phenomenon observed, which are discussed in this thesis.

These ER fluids were then tested in the fabricated model for their damping characteristics after mounting the model on the shaker table and with the application of an electric field through a variable high voltage supply. Both AC and DC supplies were used in conducting the experiments. The transmissibility characteristic curves were plotted and analysed.

In the last stage a new combination of ER fluid was tested with the same model, repeating the same external constraints except that the supply used was only AC. The thesis has been organised in the following manner. Chapter 2, deals with the phenomenon "Electro-Rheology", the effects of the dependent and the independent variables on the variation of viscosity and their side

effects in the form of electrical properties. Chapter 3 deals with the design and fabrication of the model in use. Chapter 4 deals with the experimental set up, instrumentation used, processes involved in making the ER fluid, and the experiments performed. Chapter 5 presents result and discussion. Chapter 6 concludes with a small brief on the scope of further work.

CHAPTER 2

ELECTRO-RHEOLOGY

Electro-rheology is the phenomenon in which the rheology of certain kind of Dielectric fluids is modified by the imposition of electric fields. This phenomenon is reversible in nature, without any chemical interaction and formation of by-products. In this chapter, we deal with the basic nature of the fluid, a brief historical background, definition and the influence of important variables such as field strength, shear rate, composition, temperature and field frequencies under Rheological properties. In the latter part of the chapter we have tried to analyse the effects of certain variables on the electrical properties such as dielectric strength, dielectric constants, dielectric loss, conductivity etc. to give a better logical understanding of the mystic fluid. The chapter concludes with an overview of its present and future applications.

2.1 Electro-Rheology

It is the phenomenon in which the Rheology of the fluid is modified and

controlled by the imposition of Electric fields. The factor in Rheology which forms the study is the viscosity of certain dielectric fluids. The apparent viscosity of the fluid is controlled with the application of high electric fields. On the removal of these fields the fluid behaves as the original fluid with its original viscosity and thus making the process reversible.

This apparent and abrupt change in viscosity was first observed in 1947 by the father of Electro-Rheology, Wills Winslow and thus is also called as "Winslow Effect"[1]. Though this subject was of interest for many years, but it is now that some dedicated work is being carried out in this direction.

2.2 Definitions

Electro-rheology is the phenomenon in which the rheology of the fluids is modified by the imposition of electric fields[10]. In other words, the Electro-rheological effect (ER) refers to the abrupt change in the viscosity in certain suspensions on the application of electric field [12].

Electroviscosity or Electro-rheology is defined as an essentially instantaneous reversible change in the apparent viscosity when a fluid is subjected to an externally applied electric field [5].

The (ER) effect refers to the abrupt change in the viscosity in certain suspensions on application of electric field [5].

A composition which is substantially unresponsive to a magnetic field but which readily responds to an electric field by a significant increase in the viscosity and in resistance to shear [4]. This effect is also called as the "Winslow Effect" on the name of Wills M. Winslow, who was the first to report this effect and patent it in the year 1947.

2.3 Brief History

It was as early as 1896 that these electro-viscous effects were noticed. It was Duff who first reported this effect in 1896. He had studied these effects of electric field on glycerine, castor oil and heavy paraffin and observed very

small changes in the viscosity [5]

Most of the work on electroviscosity was done by Björnstahl and Snellman[5]. Snellman studied the electroviscous properties of selected polar and non polar liquids and colloidal dispersions of metals and sulphur in dielectric liquid and reported changes in viscosity. In 1935 Dobinski also showed and reported the electroviscous effects [5,12]. Andrade worked on the investigations of Dobinski and found that certain polar conductive liquids increase their viscosity when subjected to electric fields but non polar and polar non conductive liquids are not affected. He attributed his results to a charge accumulation mechanism which was postulated to cause clustering of polar molecules and hence, increased viscosity. But these effects noticed were very small.

It was in 1947, that Winslow reported it and subsequently patented it. He reported that certain suspensions of solids in liquids show large reversible electroviscous effects [1,5,10,12]. This effect subsequently is known as the Winslow effect. He reported that when insulator liquids which suspend powdered solids are filled between two electrodes, the electrodes attract each other under an applied voltage. He explained that the Winslow effect is caused by induced fibrillation of the particles under an electric field. The dispersed particles move in the fluid to form webs or chains mechanically linking the electrodes, resulting in an apparent increase in the viscosity of the fluid[1,7].

2.4 Theory of Electro-Rheology

The proposed mechanisms for the ER effect which are highly acclaimed are:

- (I) particle interaction and fibrillation theory (Fig 2.4)
- (II) double layer deformation and overlap theory (Fig 2.5)

(I) Wills M. Winslow, the father of the ER , was the first to postulate as to how this effect occurs. Winslow first observed this behaviour and attributed the rheological changes to the structure which he presumed provided necessary mechanical linkages between the electrodes. Microscopic observations of these

fluids have also shown that upon application of electric field the particles in the fluid form chains, bridging the gap between the two electrodes. This effect was also observed by Pohl [12]. Direct observation of particle chains in electric field has shown that, at a given time after application of the field, the chain length increases with increasing field strength and particle concentration. These effects may be understood by considering the effects on the polarisation forces between the particles [12] .

(II) The primary mechanism is an induced polarisation of the double layer surrounding each particle. This double layer is the water layer which encompasses the whole particle as a sphere. Application of the electric field causes movement of the double layer relative to the particles, in the direction of the field toward the electrode having a charge opposite to the mobile ions in the double layer. Interactions between the distorted double layers and their associated charged particles, and the repulsive electrostatic interaction between double layers, therefore, increases . The resulting electrostatic interactions of the distorted double layer in the medium of low dielectric constant require the dissipation of additional energy on application of a shear stress normal to the direction of the field induced distortion .This increased energy dissipation gives the electroviscous effect [5,12].

2.5 Electro-Rheological Fluid

Electro Rheological fluids are basically dielectric,colloidal fluid and thus show dielectric like properties in addition to colloidal properties

This fluid is a colloidal dispersion of a powdered solid phase of a high dielectric constant in a base fluid of low dielectric constant. Water (generally for aqueous system) is added to the fluid to ionise the particles and cause interfacial polarisation due to which these particles readily react to an electric field. Some additive in the form of a surfactant or an active dispersing agent or an, anionic or cationic additive is added as per the nature of the dispersed phase, for the stability of the fluid and also for the formation of micelles for easy bridging and transportation of these particles [12].

Not all dielectric fluids show this phenomenon and neither it is a characteristic property of a certain class of colloidal suspensions. Andrade [2] found that certain, but not all polar conductive liquids increase their viscosity when subjected to electric fields. The non-polar and polar non-conductive fluids did not show this effect. Since negative results are generally not reported, the classification of any particular class of fluids could not be undertaken.

The only classification which has been in force is the aqueous and non-aqueous(dry) ER suspensions. The chemical nature of the particles and their water retention or adsorbent properties play a very vital role e.g. silica suspensions fail to operate or do not show the ER effect when these are used dry. But the same combination of fluid shows an enhanced ER effect when the fluid has some water content. The water has to be adsorbed on to the surface for the effect to show but if the water is adsorbed inside the particle again, the Winston effect is not seen[7]. There are some fluids in which the dispersed phase already has water adsorbed on to the surface thus requiring no additional water or very little quantity of water e.g. starch, cellulose etc.

2.6 General Characteristics of ER Fluids

(i) Viscosity

The fluids have or should have very less viscosity at zero field conditions and large under the application of electric fields. They should start operating at even low electrical fields, thus needing a high concentration of dispersed phase. But this high concentration increases the viscosity of the fluid. Therefore, a balance has to be maintained between the concentration and the viscosity.

(ii) Temperature

The fluid should have a wide temperature range of operation and also a high boiling point and low freezing point.

(iii) Stability of Dispersion

The fluid should be stable and not prone to sludging or sedimentation, in turn increasing its shelf life and long layoff periods. So the fluid should be designed as per the density matching of the dispersed phase and the liquid

phase.

(iv) Purity

The fluid should not greatly alter its property due to unwanted addition of impurities, as it would start rendering the fluid ineffective.

(V) General Properties

The fluid should be non-toxic, non-explosive and non-flammable. It should also be non-corrosive and non-abrasive to the working parts. The fluid should not have properties of oxidation and also solidification if kept for longer periods.

(vi) Power Consumption

The power requirements should be low for which the conductance and permittivity should be kept as low as possible. Thus the purity of the fluid should always be maintained.

2.7 Electro-Rheological Properties

In this part of the thesis, we will be summarising the common rheological properties of some of the fluids generally reported. Many independent and dependent variables/parameters affect Electroviscous properties. These have been discussed below under the headings - Rheological, Chemical or Constituents and Electrical Properties.

2.7.1 Rheological Properties

2.7.1.1 Effect of Electric field on Apparent viscosity or

Electroviscosity

This is one of the most important factors or is the cause for inducing ER phenomenon. It has been reported [1-13] that with the increase in the applied Electric field, the apparent viscosity increases under a given set of conditions. The Electroviscosity increases with the increase in the field strength, upto a limit where the electrical breakdown or the dielectric breakdown occurs, resulting in drawing of heavy currents. The apparent increase in viscosity varies as the square of the field strength [5]. This process of change in Electroviscosity is

a reversible phenomenon and upon the removal of the fields or voltages, the viscosity decreases instantaneously. It has also been reported that this phenomenon is field dependent rather than voltage dependent [10].

Electroviscosity is not a bulk phenomenon but this apparent change in Electroviscosity is restricted in the regions of high Electric field. So, the change in apparent viscosity, at very high fields shows a combination of friction and flow, i.e., in terms of damping, coulomb and viscous damping. There have also been reports of certain fluids even solidifying at very high field strengths. The coulomb damping starts to predominate the viscous damping at this stage [13].

In case of vibration dampers, a certain combination of fluid solidified at low operating frequency ranges, and exhibited non-linearity in the velocity profiles (as overlaps or kinks at the peak), at field strengths of about 2kV/mm and above on the application of DC fields. This effect occurs on the application of both DC as well as AC fields [10]. But it occurs more predominantly with DC fields [6] due to a unidirectional induced polarisation effect, which is the root cause for this effect.

It is reported [10], that though the dielectric breakdown places an upper limit on $E(\text{field})$ but even at fields below this level saturation occurs in the Electroviscosity effect. This may be due to high conductance and current flow which in turn causes the voltage to drop across the electrodes. Alternately, the particles experience low fields as compared to the applied voltages so as to saturate the effect. This tail off, of the effect is exhibited due to complete saturation of polarisation of the particles at high fields causing a saturation in Electroviscosity.

2.7.1.2 Electric Field Frequency

The electric field frequency ' f ' also has a large effect on the Electroviscosity, as reported by many authors. Though, summarily, very low ' f ' does not have much effect on the Electroviscosity[10], but as ' f ' increases within the ranges of 10^2 to 10^5 Hz, the ER effects rapidly declines. Thus AC fields at frequencies

(normal working range) of 50 to 60 Hz show more or same effect as those comparable with the DC fields.

The decrease in electroviscosity with increasing 'f' at constant fields, has been explained on the basis of charge migration or fibrillation theory proposed by Winston Winslow[3,5,12]. The time available for charge transport in one direction per half cycle decreases exhibiting the full migration or polarisation of the ions and leading to a loss in Electroviscosity. At zero frequency, corresponding to DC fields, more time is available for the charge transportation thus helping to reach a fully polarised state. So, the electroviscosity is maximum at that frequency, when the time required for full polarization is less than the time period of the operating fields.

2.7.1.3 Effect of Shear Rate on Apparent Viscosity

When electric fields are applied, it is evident [5] that the apparent viscosity is larger at low shear rates or shear velocities. Electroviscosity is also a direction dependent phenomenon and only occurs whenever the field is applied transverse to the shear. No effect on the apparent viscosity is reported when the application of field is in the same direction as that of the direction of the shear[5].

All practical applications of Electro Rheology are direction dependent. The use of this phenomenon,(as it is a part of this thesis) in conventional vibration dampers has been explicitly highlighted in one of the papers [13]. It is discussed briefly here.

The two mechanisms for damper configuration utilising the directional dependancy of the effect, are (a) shearing fluid mode (b) pumping fluid mode. This thesis is based on part (a) where the fluid is sheared between the cylinder and the piston acting as two electrodes. In the valve mode, the fluid is pumped between the two static electrodes to generate a resistance in flow and generate a pressure difference which would vary with applied field strength.

Recent publications have negated the dependence of electroviscosity on the shear velocity[9] and have reported that apart from minor deviations at

shear rates below .01/s, the shear stress were not dependent upon shear rate. The shear stress here is the measure of the apparent change in viscosity, i.e. higher the shear stress higher is the Electroviscosity. The same paper also states that the shear stress is essentially constant upto a shear rate of 0.33/s. Thus, the ER fluid is to be treated as a SOLID provided the Electric field is strong enough to cause solidification.

It has been reported [5,10] that the field enhanced apparent viscosity is not dependent on shear velocity γ , and there is no evidence of decrease in electroviscosity with increasing shear velocity. The shear velocities also affect the dielectric loss and it would be dealt separately under a different sub-heading later.

2.7.1.4 Effect of Temperature

These fluids are very sensitive to temperature variations and so far have not been classified under different temperature conditions due to the mystical and random behaviour of different fluids to temperature.

Though, many authors have reported an increase in Electroviscosity with increase in temperature of silica dispersions but their effects have not been quantified. It has been reported [10] that certain silica dispersions showed a four fold increase in Electroviscosity with change in temperature from 25° to 65° C. Other authors have reported enhanced viscosities at lower temperature of starch colloids with best results between 20°C and 30°C.

The temperature is the main cause behind the change in the dielectric and electrical properties of the fluid. Complex and non-uniform results with variation in temperature have been reported for different fluids and fluid concentrations.

The ER effect is nullified or it ceases to exist at very low freezing temperature [10]. Also, many aqueous fluids showing ER phenomenon become inoperative at high temperatures due to the loss of water from the system, subsequently resulting in the loss of the double layers, which promote the effect. The zero field viscosity of the medium is less at higher temperature and thereby increases the mobility of charged species. The rise in temperature enhances the electrical

energy to polarise the diffused layers and thus improves the mobility of the polarised ions at low fields. Thus, the induced polarisation effect of the double layer is higher at higher temperature [5,6], resulting in increased electroviscosity.

2.7.1.5 Effect of Electrode Gap

The electrode gap does not really affect the electroviscosity [5], as it is the field and the safety of the equipment which decides the electrode gap. The electroviscosity is a bulk phenomenon [between the two electrodes] and is largely dependent upon the fields and the concentration of the dispersed phase. The equivalent Electroviscous effect can be accomplished at even low applied fields, by increasing the concentration of the dispersed phase, thus, suggesting the low priority given to the electrode gap for the increase in the electroviscosity. In case of equipments using ER fluids this may be the main cause of worry, as it is an engineering challenge to maintain very small electrode gaps with no compromise in the operation and application with low voltage equipments.

2.7.1.6 Effect of Surface Area

For enhanced ER effects at lower fields the surface area plays a very important role. The higher the surface area the greater is the increase in electroviscosity, as the area for polarisation and mobility of the ions is increased. But this may also lead to high capacitance or accumulation of charge, leading to very high conductance. Due to the high charge density the dielectric loss also becomes higher leading to higher power consumptions. Large contact area is also not feasible due to their increased bulkiness and balancing problems. The contact area, can be increased by using all the optimum space keeping in mind the necessities for the application of high fields, and the direction of the shear stresses which always have to be normal to the field to get the best plausible results.

2.7.2. Effect of Constituents on Rheological Properties

2.7.2.1 Concentration of Dispersed Phase

The concentration of dispersed phase has a very large role to play in the effectiveness of the ER fluid .

The dilute concentrations of silica with volume fraction less than 0.1 do not show significant effect even at large field strengths. But as the concentration of silica is increased up to a particular limit, slowly the effects get more pronounced. Increasing the silica concentration certainly increases the viscosity of the fluid, affecting the fluidity and also the abrasive nature of the fluid. On the other hand high concentrations of silica can lead to high field tail offs. For effective working, generally the silica concentrations should be in the range of 0.1 to 0.4 volume fractions [10]. Higher silica concentrations can or may give better results even at low fields but on the penalty of the saturation of effects at low field strengths.

It has been reported that increasing the silica concentrations increases the efficiency of the fluid to work at higher shear rates[10]. Increasing the silica concentration increases the electroviscosity at constant field strength and shear rate conditions compared to the dilute suspensions.

Electroviscosity is a bulk property and thus the effect of concentrations have a major role to play [5]. With increasing the concentration of silica, more and more ions are polarised at the same field strengths to form more chains or to have more number of mobile charge carriers to give a higher electroviscosity compared to the dilute fluids. The electroviscosity keeps on increasing with increasing silica concentration but this increase in the silica concentration puts a limit on the dielectric strength and the dielectric constant of the fluid. Very high silica concentrations can even lead to an early dielectric breakdown of the fluid.

2.7.2.2 Effect of Water Concentration

Water also has a very important role to play in the efficiency of almost,

all ER fluids. Small amounts of water are added to the fluid to make the dispersed phase particles adsorb water on the surface for generating the double layers which are the prime cause of the electroviscous effect. The most plausible explanation for the necessary presence of water, is that water acts as a vehicle for mobile ions, increasing the interfacial polarisation and leading to the creation of electric double layers [7,12]. Another way in which water may contribute to the ER effect is by enhancing the adhesion between particles due to property of high surface tractions. When an electric field is applied, the field tends to pull the mobile ions and their carrier liquid tangentially. This movement causes the water to be repelled from the pores of the particles. If the water is confined to high field regions between particles, it forms a bridge between particles, thus strengthening the inter particle interactions[12].

Although, it has been reported [10,12] that the presence of water is a necessity, yet water should be added in the fluid in just sufficient amount. The amount of water needed in the system is still not very clearly understood but all aqueous fluids work best between 5% to 10% W/W[7,10,12]. If water quantity is kept below 5% the effects are not as well pronounced, as observed when the quantity is well within this range. The absence of water in aqueous fluids leads to drying of the fluid and in turn failure in formation of double layers causing a loss in electroviscosity.

If water is in excess, the effect is lost as the double layer and the polarisation phenomenon are negated causing the inter-particulate high strength bonds to weaken and also leading to a loss in electroviscosity .

Even temperature affects the water concentration and in turn the electroviscosity. The viscous and conductive heating of the fluid causes the eventual loss of water which is also a cause for the loss of effectiveness [10].

2.7.2.3 Adsorption

The double layer formation due to the ionic polarisation of the particles is based on the adsorption principle. Adsorption of water is of two types : one is to adsorb water on the surface of particles and the other is to adsorb

it in the inner part of the particles. So, when the amount of adsorbed water is small and is adsorbed in the inner core of the particles, the double layers are not formed and the Winslow effect never occurs [7].

To summarise, generally all fluids need a certain amount of water content, but within a prescribed range, to form the needed double layers. The important fact is adsorption of water on to the particle surface and not in the particle to show the needed effect. Though, there have been reports [10] of dry ER fluids but we will not be digressing to this complex field.

2.7.2.4 Effect of Dispersed Grain Size

Not much literature is available about the viable grain sizes to get the optimal results. As per references [10,12] the dispersed phase particulate sizes fluctuate between ranges of 0.04 to 50 micron. Though larger grain size particles would show the ER effects, but their response would be slow on application of electric fields[12]. The lower grain particle sizes may be affected by the Brownian motion forces and would hinder the action of the electric field forces, resulting in a loss of the effect. The problem with higher grain size particles is sedimentation due to both gravitational and centrifugal forces. These problems can be overcome by dispersing the powdered phase in a fluid of matching density and by adding a good non-flocculating and dispersing agent. But there is an upper limit for the particle size, which is generally kept as one-tenth of the electrode gap [10].

2.7.2.5 Particle Shape

Similar to size, not much literature exists about the optimum particle shape, but the reports predict a minimal change in the ER effect with changing particle shape[1,6].

2.7.2.6 Effect of Inter Particulate Distance

This should form a very important factor while making an ER fluid, but not much has been really reported for the preparation of the fluid. Coulomb interactions between polarized double layers require an inverse relationship

to the distance separating these changes and the Electrostatic forces. So the interaction varies as the square of the distance separating them is the foremost point. These interactive forces between the particles are directly related to the electroviscosity. It has been reproduced here for convenience [7]. The dispersed phase particles were considered spherical particles in simple cubic and closed packed configuration and the inter double layer distance 'X' was calculated as

$$\text{Simple cube } X = d [(0.8060 / \phi^{1/3}) - 1]$$

$$\text{Close pack } X = d [(0.9045 / \phi^{1/3}) - 1]$$

d = particle diameter + 2 (double layer thickness),

ϕ = experimental volume fraction of disperse phase.

δ = proportionality constant relating inter-particle distance to particle diameter, and is represented by the terms in brackets in the formulas.

It has been observed that δ decreases with ϕ as shown in Fig 2.1. The value of δ was assumed to be directly related to the distance between polarised layers on application of transverse shear. After plotting of experimental data the electroviscosity was found to vary as the square of the electric field and

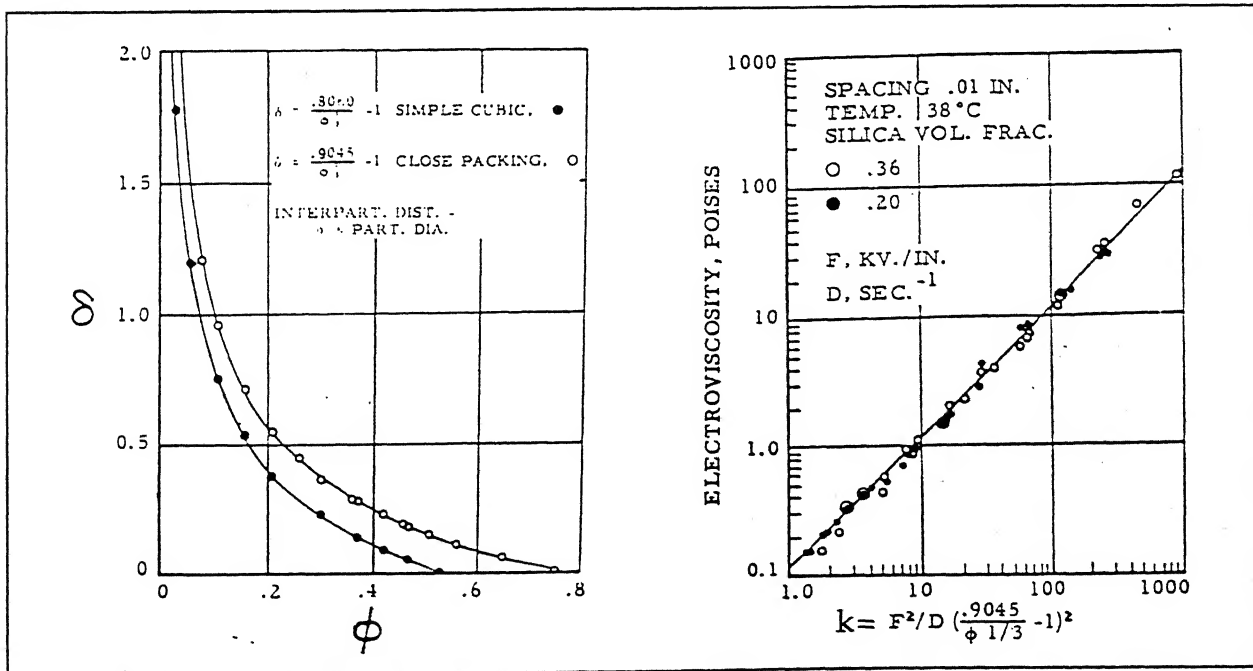


Fig 2.1

Fig 2.2

inversely proportional to the shear velocity at a particular silica concentration. The results are shown in Fig 2.2.

$$\text{where } k = F^2 / \{D(.9045 / \phi^{1/3} - 1)^2\}$$

The results show that electroviscosity varies inversely to the square of the distance separating the double layers (calculated theoretically) and experimental volume fractions. This confirms the double layer polarisation mechanism. This inter-particulate distance is actually related to the concentration of the dispersed phase, already discussed previously in this chapter and shows the same effect. Reports have shown that increasing concentrations of particles at a given electric field strengthen the ER effect. It has been reported that [12] an increase in shear modulus (here taken as electroviscosity) by 2 decades takes place with increase in volume fraction from $\phi = 0.1$ to 0.2 at 1 kV/mm field strength at very low frequency of 1 Hz of diatomite in transformer oil. On the other hand only a three fold increase in the shear force was reported upon doubling the volume fraction[12]. Moreover, at high field strengths the shear force decreased with increasing concentration of dispersed phase as already discussed previously.

2.7.2.7 Additives

With systems where additives are necessary, water can be replaced by alcohols, formamide, dimethylamine, ethylene glycol or other polar liquids [10,12]. It is suggested that these are added to enhance ionic conductance or to provide an environment for ionic conductance and also to provide high surface tensions which enhance the charge formation on surfaces and provide adhesion. They also enhance the particle-particle bonding strength to facilitate the ionic polarisation or double layer phenomenon.

Surfactants or active surface dispersing agents are added in certain fluids for mainly two reasons. Firstly, to increase the stability of the suspension and secondly, to create micelle bridges between particles with their tails or chains [6], in the same way as it works in soaps.

2.7.2.8 Addition of Metallic Powders

It has been reported [10,12] that certain kinds of metallic powders enhance the ER activity by increasing the local field strengths over the interparticle gaps. Dispersed metals alone are either inactive or show very small mechanistically different effects. But these work effectively only in aqueous system and are completely ineffective when dry.

2.7.2.9 Addition of Salts

There has been some evidence [10] that addition of salts to moist systems further promotes ER response. The counter ion in poly (electrolyte) based systems has major influence on ER. It has been reported that anion exchange resins which have both univalent and divalent anions of weak and strong acids are the counter ions.

2.7.2.10 Dispersing Oils

These have not been widely studied and also their role in Electro-Rheology has not been clearly defined except that they form a medium of high dielectric strength for the mobility of the polarised ions and also for formation of chains [10,12] to give the ER effect. But the following properties of Dispersing oils are desirable:

- (i) low viscosity
- (ii) high dielectric strength
- (iii) noncorrosive
- (iv) good insulating property
- (v) non-volatile.

Apart from these, the liquid should have low dielectric constant so that the dielectric strength is high and it can withstand high fields without any dielectric breakdown. But polarity of base fluids is still not clear and is not reported properly, although a lot of polar fluids have been listed [10].

2.7.3. Electrical Properties

The fluid is a colloidal dispersion of a high dielectric constant dispersed

phase in a low dielectric constant medium [oleogenous fluid] thus, rendering it a dielectric in itself. Once we consider the fluid as a dielectric, it has measurable electrical quantities such as conductivity, dielectric constant or permittivity, dielectric strength and dielectric loss. The analysis of these quantities would give us some insight as to the behaviour of these fluids on the application of high fields. The results discussed are available for silica suspension (most commonly and widely used).

2.7.3.1 Conductivity

All aqueous and dielectric fluids show some conductivity which is considered a requirement or a necessity. As reports suggest, a small or finite conductivity is required for electroviscous effects to appear [6]. Especially, when dealing with DC fields, small currents were observed to flow with increasing electroviscosity. This can be attributed to the transportation of the mobile charge carriers which must be available in ER fluids for the double layer phenomenon to occur. So, conductivity is an inherent part of the electroviscous phenomenon.

Klass and Martenik [6] have reported this phenomenon with DC fields and have reported that electroviscosity is nil or appreciably less at very low fields, for very small currents. But as soon as the energy barriers, which might be restricting the flow of the mobile ions (the coulombic electrostatic forces), are overcome, conduction occurs. Thus, electroviscosity appears at the onset of current flow. As the applied field is increased further, the current flow increases linearly for small fields with higher changes in electroviscosity. With still higher fields, the current deviates from linear to higher powers with increasing Electroviscosity. This is the case for an ideal ER fluid. But, a point to be noted here is that, the current is not a measure of the ER effect.

At saturation of the electroviscous effects, conductivity can increase with increase in field without any appreciable increase in the electroviscosity. This tail off is due to the saturation of polarisation of the particles at the low fields. It can also be attributed to the decrease in the effective field strength

due to flow of current. The effect and current vs. DC voltage has been shown graphically in Fig 2.3 (a reproduction from the reference [6]) to quantify the effect.

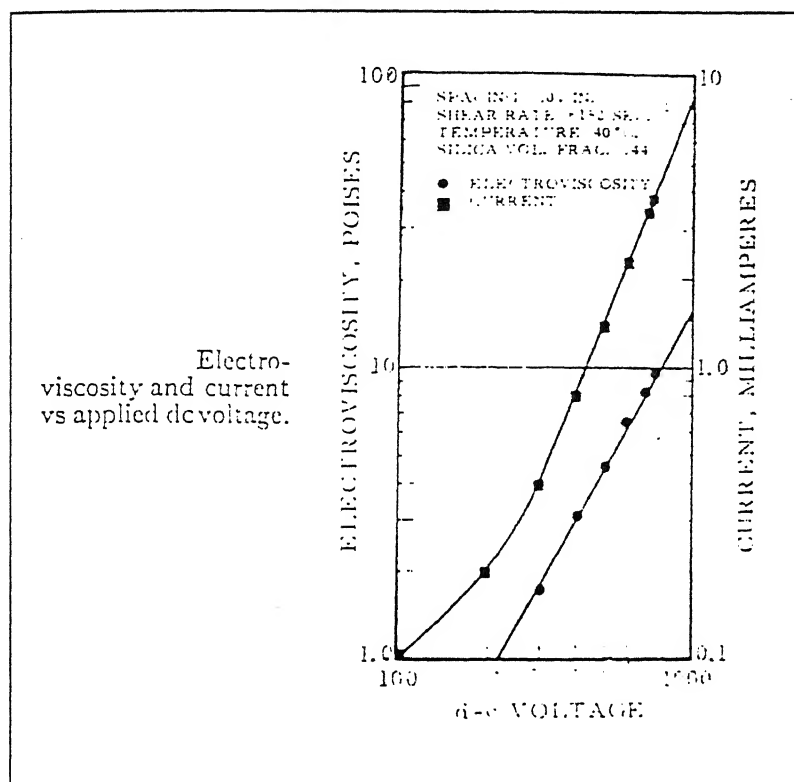


Fig 2.3

(i) Effect of Silica

concentration

The dispersed phase (silica) are finely powdered particles of high dielectric constant and strength and thus, have a very large effect on the electrical properties with any variation in concentrations.

Silica, being an insulator, shows low conductivity and low

dielectric loss. But it has been observed that silica [2] fluids have a high dielectric loss and conductivity. The high dielectric loss and conductivity can be attributed to the charge on the particles due to the formation of double layers by adsorption of water on the particle surface. This strongly adsorbed water layer may constitute the conduction path. Thus, all silica fluids show some conductivity and dielectric loss even when subjected to very low fields.

Whenever the concentration of silica is increased in a fluid, the dielectric constant of the fluid is increased alongwith an increase in dielectric loss or the conductivity of the fluid. In dilute silica concentrations, the particles as well as the double layers are far apart. Thus, high fields have to be applied for formation of chains to cause high electroviscosity. So dilute fluids have a high dielectric constant (measure of degree of polarisation) and high dielectric loss. Without applying any field, when the particle concentration is increased upto a point, interaction of the double layers commences. On the application

of fields, the polarisation of the double layers is higher due to higher particle concentration, leading to higher electroviscosities. With still higher concentrations of Silica, the ability to store more energy levels off (as the particles have already been polarised at low fields) leading to saturation in the phenomenon as well as in the energy level. This, in turn, also increases the dielectric loss and the dielectric constant.

But on further increasing silica concentrations, the particles start to interact causing the dielectric breakdowns even at very low field strengths (drawing very high currents). This can be attributed to the shorting of the electrodes at very high silica concentrations as the adsorbed water bridges the path for conduction. Though the addition of silica increases the dielectric constant, but its addition has to be restricted to restrict the dielectric loss.

Dry silica powders or non-aqueous silica suspension do not get polarised, with no formation of double layers. This makes nonaqueous suspensions non-responsive to the effect.

To summarize, the concentration of dispersed phase (ϕ) enhances the conductivity as more number of ions are being polarised at that field. Very high concentrations of the dispersed phase can even cause shorting of the electrodes.

(ii) Temperature

This is also another factor which increases the conductivity but with an increase in electroviscosity. Due to thermal agitation and lowering of the interparticulate attractive forces, more number of ions get polarised. This helps in the formation of more double layers resulting in an increase in electroviscosity. But, these more number of mobile charge carriers or the polarized ions cause high conductivity.

(iii) Water

Water has a very drastic effect on the electrical and dielectric properties of the fluid. One of the primary causes for the restricted use of these aqueous fluids is that water due to its conductivity at high fields generates some

amount of heat which in turn causes a loss of moisture leading to a loss of the ER effect. Secondly, high water contents can lead to an early dielectric breakdown and high power consumptions. In addition, water also leads to corrosion and deterioration of the parts.

Addition of water causes dielectric dispersion. If amount of water is less, then the dielectric dispersion does not occur and the dielectric double layers are not formed [7]. It has also been reported that addition of water increases the dielectric constant of the fluid and also increases the surface charge density, responsible for the formation of electric double layers. Due to this reason the dielectric loss of the fluid is increased leading to higher power consumption. But, nevertheless, increasing water concentration within the prescribed limits enhances the electroviscosity. Increased water content initially does increase the conductance, but at very high water contents the bulk conductance of the fluid takes over resulting in a dielectric breakdown or a stage of runaway conductance. This high conductivity decreases the field strength and in turn the electroviscosity.

Summarily, water definitely enhances the permittivity and the charge density. But, this causes a loss in the dielectric strength of the fluid. Higher concentrations of water further increases the dielectric constant and decreases the dielectric strength, causing high dielectric losses resulting in a loss of electroviscosity, even at low fields (already discussed as tail-off). Still higher concentration of water increases the bulk conductance of the fluid causing a heavy current to flow, resulting in a further drop in electroviscosity and finally shorting of the electrodes, at very high water contents.

(iv) Addition of Salts

Apart from increasing electroviscosity they also increase the conductivity as it promotes the number of mobile ions in the fluid.

(v) Effect of Shear Velocity

It has also been reported that shear velocities also effect the conductivity [6,7]. The shear stresses applied normally to the field perturb the double

layer formation and polarisation phenomenon. At very low shear rates/shear velocities, the polarisation is maximum with a high increase in the electroviscosity. This increase in polarisation increases the conductivity. Polarisation decreases with increase in shear velocities, as the disturbance decreases the polarisation and the formation of double layers. Therefore, with increasing shear velocities there is a drop in electroviscosity and conductivity.

Similarly, when using AC fields the effects on the conductivity are the same as with DC fields. With increase in shear velocity, the dielectric losses are reduced. But if polarisation is the only conductive process then increasing shear rates would decrease the loss at frequencies (AC) higher than the relaxation frequency, because polarisation is then reduced [6]. Thus there are three conduction processes at low frequencies: (a) one is frequency dependent which depends upon the f_c , the characteristic frequency for the resonance condition when frequency matches the relaxation frequency, (b) shear-dependent, (c) due to the fluid itself. It has also been reported in the same paper that if shear-induced conduction predominates, then it will be an opposite process where the dielectric loss is increased at high shear stress rates [6,7].

Summarily, conduction is an after effect of the polarisation on the application of fields. The electroviscosity appears at the onset of polarisation, and thus the current starts to flow at the instant of change in the viscosity of the fluid. Increase in shear stress decreases the dielectric loss but up to f_c and the conduction is dependent upon frequency (AC), shear-stress and the inbuilt conductivity.

2.7.3.2. Dielectric Constant

At low shear velocities, the dielectric constant changes very feebly. Generally, at low shear rates the chain formation and aggregations of the particles are more and thus the dielectric loss is higher and the dielectric constant is decreased with decrease in shear rates. On parallel lines of dielectric loss and conductivity it has been reported [6] that with an increase in the dispersed phase concentration, the dielectric constant of the fluid is increased along with an

increase in charge density. This is only at low operating frequencies. Addition of more water, as discussed earlier, increases the dielectric constant of the fluid subsequently leading to high dielectric loss. Temperature upto certain limits, enhances the permittivity or the dielectric constant, but decreases the dielectric strength of the fluid.

One of the most important factors on which the permittivity of these fluids depends is the frequency 'f'. The relative permittivity is a complex phenomenon under flow and at high fields. This modified permittivity is under shear and flow and is termed as Flow Modified Permittivity [10]. This phenomenon is highly dependent on the frequency of the applied fields and on the shear stresses and is observed at high field frequencies and high shear rates.

2.7.3.3 Electrokinetic Phenomenon

It is the phenomenon where the fluid starts to behave as a DC cell under high shear. It has been known to occur in dispersions having double layers. Streaming potentials and currents are produced when these fluids are subjected to flow in capillary tubes. A potential difference arises when the stream carries with it the heavy mobile part, the ions, along with the double layers sticking to the walls of the tube. This back conduction of charge carriers causes current to flow [6].

This kind of phenomenon is also observed in the ER fluids which work on the principle of induced polarisation of double layers. When these fluids are sheared, the shear stresses cause relative movement between the particles and the lighter mobile ions in the double layer. This in turn leads to the "Electrokinetic phenomenon". This was also shown experimentally [6] with a sudden drop in the ohmic resistance when shear is applied. This phenomenon is attributed to the fact that the loosely held ions are broken from the double layers near the shearing walls. A steady state current and voltage were produced and power output measured was 6×10^{-8} watts.

2.8 Applications

Possible areas of application include ER clutches, brakes, hydraulic valves, active vibration damper systems, wide band power vibrators, chucks etc. The work on these systems are also in progress with many of them already on the commercial testing stage[10].

Reports have shown that many of these devices especially being used in the automotive industry have been on commercial test beds with scope of improvements in design. Certain other feasible ER fluid prototype devices are tension control clutches, controlled torque screw drivers, variable engine mountings, engine dampers, high voltage power supply valves and variable modulus beams[11].

2.9 Summary

Keeping the above factors in mind before making a fluid would surely improve the quality of the fluid alongwith a good understanding of the fluid responses under different conditions and different applied fields.

Although it is nearly impossible to produce an ideal fluid with extremely low power consumptions (as per the loading requirements and the source system constraints) but a good ER fluid should have the following pre-requisites.

The purity of the fluid is of prime importance. The fluid should have low dielectric constant, high dielectric strength and a very high ohmic resistance. The appropriate concentrations of dispersed phase and water should be maintained so as to limit the dielectric losses within the current constraint of any power supply unit and to reduce the power consumption. As there are so many dependent and independent factors affecting the ER response, the optimum solution has to be chosen to make the fluid behave under the applied electric fields.

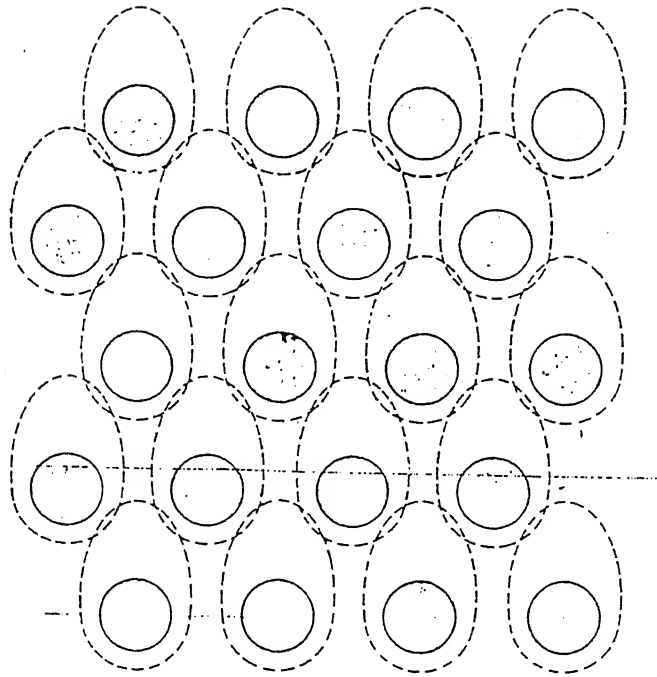


Fig 2.4 Chain Formation

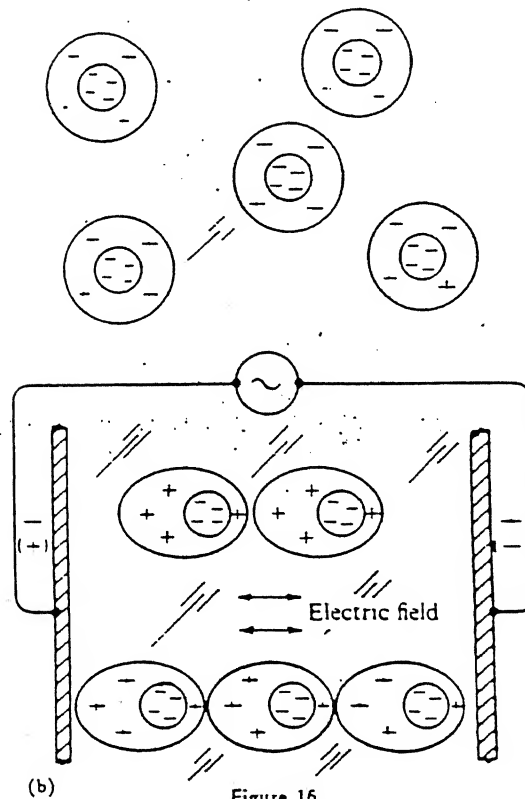


Figure 16.

Double layer polarization (a) before, (b) after applying an alternating electric field. Reproduced from [142].

Fig 2.5 Polarisation of Double Layers

CHAPTER 3

DESIGN AND FABRICATION

This chapter deals with the design and fabrication of the model on the basis of the operational and safety requirements on the application of High Voltages. The chapter also deals with some problem areas and some modifications incorporated in the model for a more efficient model.

3.1 Design

The design features have been discussed under different subheadings to briefly quantify the design aspects. The main feature of the design was to consider the piston and cylinder as two electrodes, as suggested and reported in references [8,13]. The model works on the principle of shearing mode with the fluid being shared between the cylinder and the piston. The fields are applied normally to the direction of shear.

3.1.1 Mechanical

The primary requirement was a need to restrict the vibratory motion of the spring mass assembly to a single degree freedom system, maintaining the running clearances, with restrictions to any slight tilting of the piston during

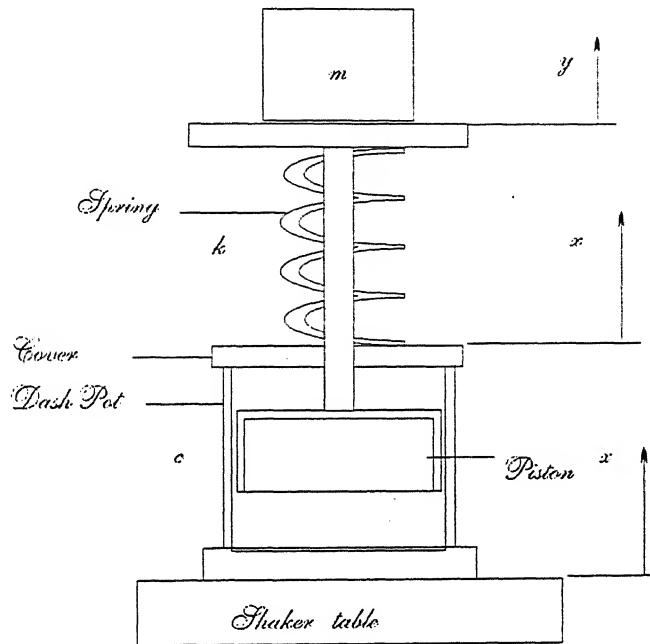


Fig 3.1

operation.

The setup (Fig 3.1) is a single degree of freedom mass, spring and dashpot assembly with the spring mounted on the cylinder cover. The piston is attached to the loading platform with the help of a screw. The loading platform is mounted on the spring. The piston rod passes through the piston guide bush made on the cover. The assembly works as a spring and dashpot assembly in parallel and can be modelled as in Fig 1.1.

To maintain the single line motion, a lot of stress was laid on the running clearances and the concentricity of the model. Additional support in the form of a cylindrical guide was attached to the model's loading platform to restrict any unnecessary tilting of the load while in operation (Fig 3.6).

Another feature, which was given weightage, was the low initial viscous damping of the system. It was reduced appreciably by drilling through and

through holes in the piston for easy flow of the fluid. The surface area plays a major role in Electroviscous phenomenon, as discussed in the previous chapter. Hence the piston was designed as a cup. It was made hollow in the inside for the prime reason of reduction in weight. Finally, the model was designed to be robust and to withstand high resonance amplitudes.

A piston rod bush is also designed to offer least amount of resistance to the piston rod while in operation by cutting grooves in addition to maintaining a running fit. Holes are drilled in the outer guide cylinder to reduce pneumatic damping which may occur due to entrapping of the air in the guide cylinder.

Though no rigid clamping arrangement is made for the mounting of the spring, but the spring is mounted on the cylinder cover as a tight fit for which an slightly oversized seat is made. The same arrangement is done on the loading platform (Fig 3.6.)

3.1.2 Electrical

The model was designed, considering the cylinder and the piston as the two electrodes for the application of high fields.

A minimum electrode gap (gap between piston & cylinder) was kept considering the requirements for application and the safety, while inducing high fields with low applied voltages. To make certain, that there is no contact between these two electrodes or between the piston and the cylinder while in operation, a teflon washer was designed and fixed on top of the piston as seen in Fig3.4. This prevents shorting of electrodes at high voltage.

The different parts, the negative electrode (cylinder) and the positive electrode (the piston), are thoroughly insulated from each other at all the areas to avoid any chances of contact, endangering safety. The base is also insulated from the shaker table by sandwiching a Bakelite sheet between the two.

The assembled working model is as shown in Photo 3.2.

3.2 Fabrication and Materials

3.2.1 Dashpot

The dashpot is a commercial copper cylinder of external dia of 57mm, height of 72 mm and an internal dia of 51.3 mm (Fig3.2). This copper cylinder

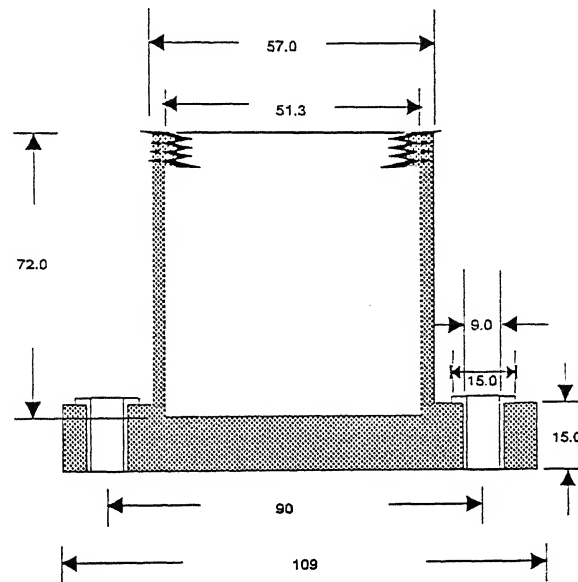


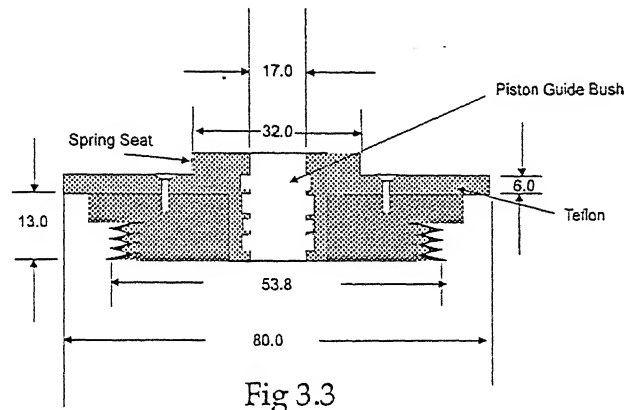
Fig 3.2

was brazed to the MS base by rapture welding of silver concentration 40%, to give the weld a smooth and strong finish. Care was taken to maintain the concentricity and uprightness of the cylinder. Then, the copper cylinder was machined to an internal dia of 51.3 mm to remove ovality, which may have occurred during brazing.

Fine internal threads of 1 mm pitch are machined on the cylinder top for securing the cover attachment and to ensure a sealing fit. Six holes are drilled on the MS base for the rig's attachment to the shaker table. To insulate the attachment bolts from the base, which would also act as electrodes, internal fibre washer's of thickness 3 mm were force fitted into these holes (Fig.3.2). For the insulation of the base, a Bakelite plate of same diameter with 6 holes and 5 mm thickness was used.

3.2.2 Cover and Piston Guide Bush

The brass cover has external threads of pitch 1 mm for securing on to the copper cylinder. It has a dia of 70 mm and an effective thickness of 13 mm



(Fig 3.3). Here, care was taken to maintain the concentricity. The piston guide bush which is the most important and was the most problematic area is of Teflon and is of 5 mm thickness. This bush takes the maximum load of tilting and friction, and was therefore, machined to a fine clearance of 0.1 mm (radially) with the piston rod. To reduce the friction at the guide, internal grooves are made so as to maintain a running fit, in addition to reduction in the contact area. The length of bush is 25mm, and is made in two parts as shown in Fig 3.3. A teflon sheet of 12 mm and 80mm dia. was machined and attached to the cover plate by counter sunk screws as shown in Fig 3.3. This sheet has a triple purpose. Firstly, the protruding teflon ends act as contact guide to the main guiding cylinder, secondly, it provides full insulation from the copper cylindrical cathode, and lastly, it provides a rigid platform for mounting and insulation of the main spring. The spring seat is machined to 32 mm dia and a height of 6 mm. This provides a tight fit to the spring base and also prevents it from tilting.

3.2.3 Piston Assembly

The piston assembly is made of brass. The piston rod is of 16.8 mm dia. and a total length of 120 mm. Steps are machined on both the sides for a

tight fit attachment to the piston and the loading platform on the top, in order to restrict them from loosening and tilting (as shown in Fig.3.4). The piston has an effective height of 24.8 mm and external dia of 49.7 mm to maintain a radial gap of 0.8 mm from the cylinder. The effective surface area

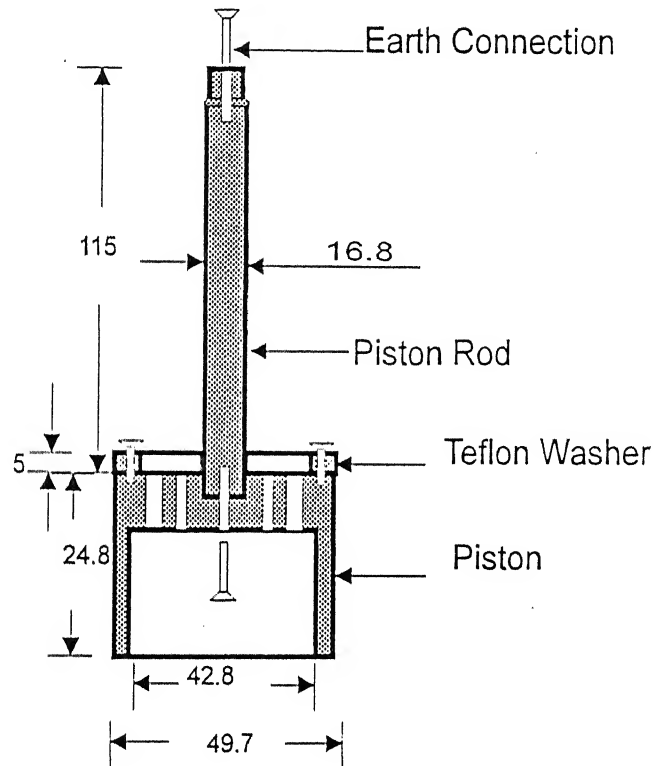


Fig 3.4

of the piston is 3870 sq. mm or 38.7 sq. cm. To reduce the weight of the piston, the piston is made in the shape of a cup. Eight holes of 5 mm dia. and eight smaller holes of 4 mm dia. are drilled on the piston top as shown (Fig.3.4) to reduce the initial viscous damping. A Teflon washer of 5 mm thickness is attached to the piston as shown (Fig 3.4), to safeguard the piston against making any contact, while in operation, with the cylinder, causing short or arc formation. The teflon washer has slits cut on its sides for easy flow of fluid to the top. The washer dia. is 51.1 mm, just enough to provide a running fit in the cylinder. The washer is attached to the piston with the help of counter sunk screws. The piston is assembled with the piston rod with the help of a counter sunk screw.

3.2.4 Loading Platform

This is a MS circular disk with a teflon and brass bush inside for a tight fit with the piston rod at the top end. The teflon bush insulates the piston rod (the anode) from the top loading platform and is around 6 mm in thickness. The loading platform has two side tapped holes for the attachment of the guiding cylinder.

The brass bush is attached to the teflon bush by dowell pins. The dia. of the platform is 87 mm and has a thickness of 11 mm. Three tapped holes of 3/16" dia are provided on top of the loading platform for the attachment of the load support at a pcd of 68 mm.

3.2.5 Guiding Cylinder

This is a MS cylinder of outer dia. 90 mm and an inner dia. of 80 mm. The length of the cylinder is 120 mm (Fig.3.5). Four holes are drilled on to the cylinder for the release of any trapped air during motion. This cylinder is attached to the loading platform by screws. This cylinder slides on the teflon ring and takes any major tilting due to uneven displacement of weight or any eccentricity and guards the main piston rod bush from overloading. The clearances with the overload rings are machined to provide a running fit.

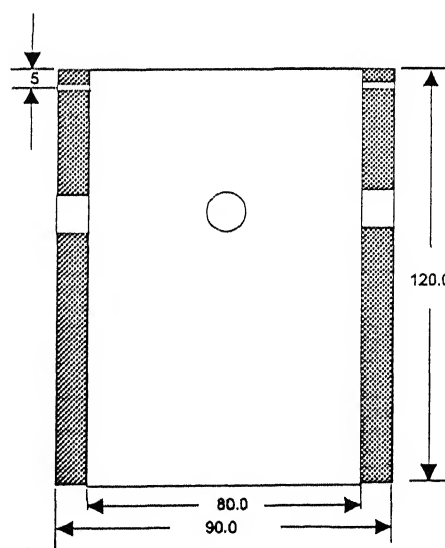


Fig 3.5

3.2.6 Overload Ring

This is basically a teflon collar which can be adjusted along the copper cylinder as per the requirement. This acts as an additional support to the loading platform while in operation and also insulates the guiding cylinder from the copper cylinder which is acting as an electrode. This is slipped on to the copper cylinder as a tight fit and then secured by four screws.

3.2.7 MS Base Plate

A MS base plate is attached to the shaker table for the attachment of the test rig. It has eight holes drilled for its attachment to the shaker table and six holes drilled for the attachment of the test rig.

3.2.8 Spring

The spring is a flat ended, compressive, helical spring of external dia. of 40mm and wire dia. of 4 mm. The length of the spring is 70mm and it has eight active coils. The stiffness of the spring was tested on the INSTRON, UNIVERSAL TESTING MACHINE and was calculated to be 11.11 N/mm.

3.2.9 Load Attachment

It has MS base with a rod(threaded) welded on top of it for sliding the cylindrical weights. It has three holes for its attachment to the loading platform with the help of counter sunk screws. It has an outer diameter of 80 mm. The welded rod is of 120 mm in length.

The parts are shown in the Photo 3.1.

3.3 Problem Areas in the Model

Though the model has worked efficiently and very effectively, but, there are still some problems to be ironed out. These are listed as below:

(i) The internal threads in the copper cylinder generally get filled up by the colloidal particles, thus creating problems in securing the cylinder cover. It leads to unnecessary wear and distortion of the cover plates and requires cleaning from time to time. Thus, external threads on the copper cylinder

with internal threads on the cover plate can be a better option.

(ii) There is no tapping provided for filling or draining the fluid, thus, requiring dismantling of the mass from time to time, making it a tedious and time consuming job.

(iii) Even though fine clearances were maintained, yet wear and tear (especially when using silica dispersion) of the brass piston rod and the teflon bush caused a play in the piston during operation. The main part to wear down was the teflon bush, being softer than brass. This has already been rectified by introducing a brass bush and decreasing the dia of the piston .

iv) No clamping arrangement has been provided for the spring.

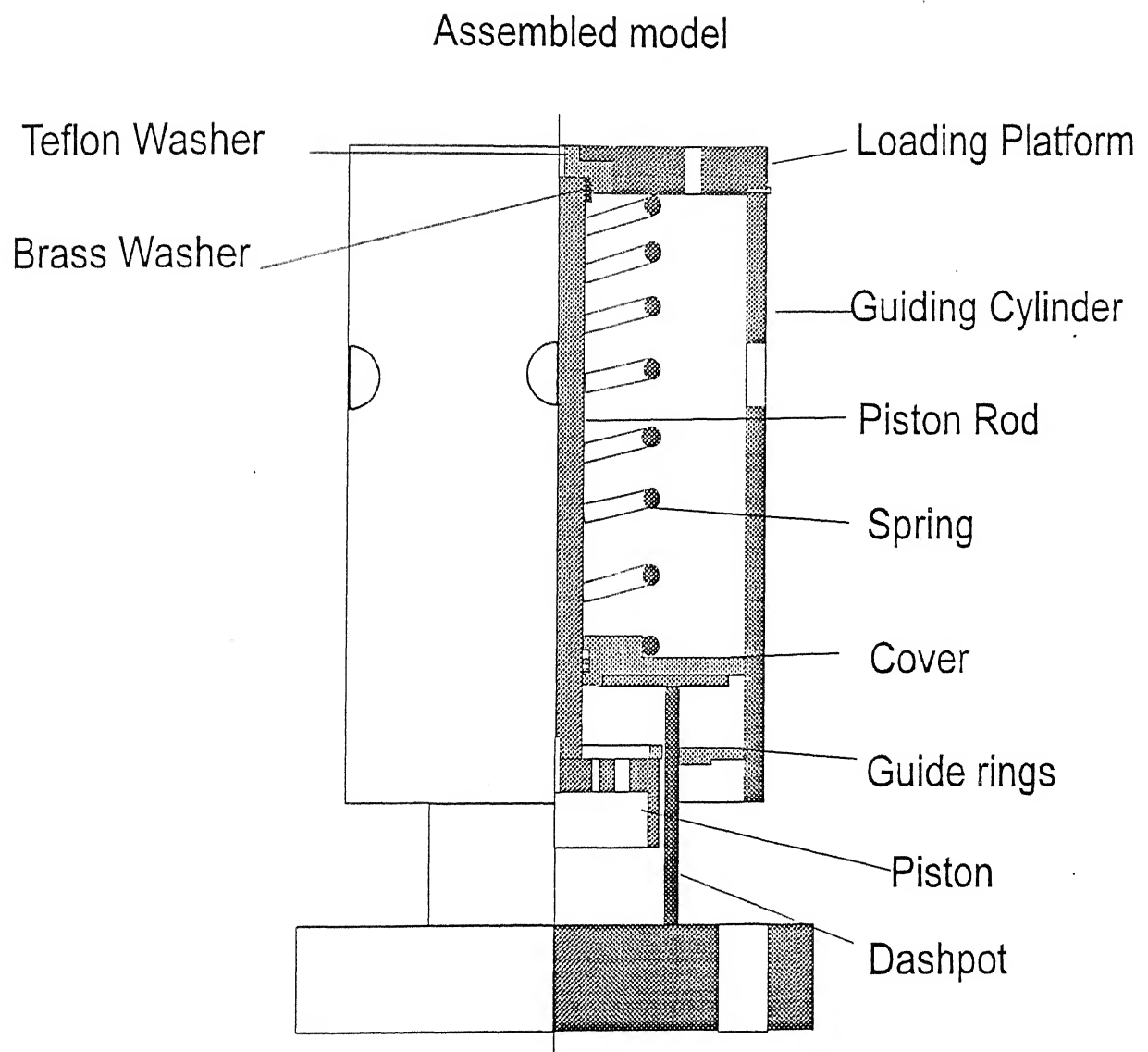


Fig 3.6

CHAPTER 4

EXPERIMENTATION

This chapter deals with the experimental setup and instrumentation. The transmissibility curves were obtained on exciting the model with harmonic base excitation after mounting it on a shaker. These curves were analysed to characterize the damping characteristics of the fluid with changing field strengths. It also deals with the parameters which were considered during the experimentation. The latter half of this chapter deals with the processes involved in making the ER fluids and also a brief on the failures encountered.

4.1 Experimental Setup

The Model (MS base) was mounted on the Vibration shaker, through a rectangular MS base plate with eight holes. The base of the Model was insulated from the base plate by sandwiching a Bakelite circular sheet of 5 mm thickness. The ER fluid was then poured into the Copper cylinder upto a desired level, such that the piston remained submerged completely on assembly. The model was assembled, and the base connected to the High Tension/voltage terminal

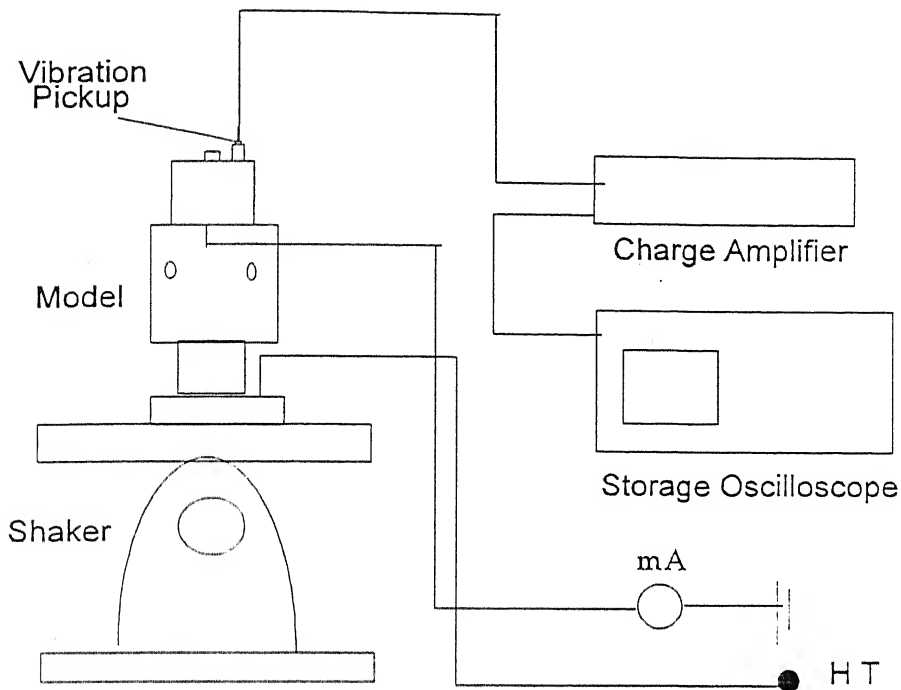


Fig 4.1

and the piston rod to the earth, with the help of the screws provided on to the model.

The necessary loads were mounted on to the loading platform, with a separate attachment and clamped by a securing bolt. The vibration pickup (an accelerometer) was mounted on top of the attached load. The signal was then integrated twice through a charge amplifier before sending to a storage oscilloscope as shown in Fig. 4.1. The fluids used were of two types, one with silica and the other with starch as the dispersed phase (Photos 3.2 and 4.1).

4.2 Instrumentation

The vibration shaker used is ALL AMERICAN STROKIE, ILL, USA, with a variable speed control. The frequency is controlled manually from a control panel. The shaker has an arrangement to change the required base amplitude from 0" to 0.150".

AC as well as DC supplies were used in the experiment. DC supply (Electronic Corporation of India Ltd., Model HV4800) was used which had a maximum current rating of 30 mA and a maximum voltage of 3000 V, with

over-current protection. A variable AC voltage supply (ALLIED ,Single Phase, 50Hz) having a maximum current rating of 45 mA RMS and maximum voltage of 5 kV (range 0-1 kV and 1 kV to 5 kV) was used. One B & K (Type 4370) accelerometer, placed at the top of the weight, was used to pick up the acceleration signals. These signals were then amplified and integrated twice to obtain the displacement signals by a B & K (Type 2635) charge amplifier. The signals thus obtained were fed to a Kikusui, Digital Storage dual beam oscilloscope. The base amplitudes were also recorded in a similar manner at the particular set frequency (Photo 4.1).

4.3 Experimental Procedure

Once the experimental setup was complete, the base amplitude was set and kept constant throughout the test. The frequency was changed and also kept constant for a particular set. The amplitude (peak to peak) was recorded from the oscilloscope at zero voltage. The voltage was then increased in steps and changes in amplitudes were recorded with each increase. This was done upto the maximum voltage which could be applied, untill the high voltage supply equipment neared the tripping current or tripped automatically. The reverse set, with decreasing voltages were also recorded for analysing the reversal change in the amplitude (peak to peak) on the viscosity and also for cross checking the validity with increasing fields. The base amplitude was recorded by placing the accelerometer on the base at the set frequency.

For the second set, the frequency was increased further and kept constant. The whole procedure described in the above paragraph was repeated and the top mass amplitudes measured with increasing and decreasing voltages. These sets were recorded with increasing frequencies well into the region where $\omega > \sqrt{2}\omega_n$.

4.4 Experimental Parameters

Certain parameters were changed to note the effects on the damping characteristics of the fluid.

4.4.1 Dispersed Phase Concentrations

The above experimentation procedure was repeated with fluids of different dispersed phase concentrations keeping the base amplitude and resonance frequency of the model constant. This was done to analyse the damping characteristics with the change in dispersed phase, on application of high fields.

4.4.2 Resonance Frequency

The resonance frequency, of the model is changed by removal or addition of the mass on the loading platform. To analyse the frequency dependence and the effect of shear velocity on electroviscosity, tests were conducted keeping the dispersed phase concentration and the base amplitude constant.

4.4.3 AC & DC Fields

As discussed in chapter 2, the feasibility of using either AC fields or DC fields was seen. DC fields were applied to silica suspension, and AC fields mainly to starch suspension. The experimental procedure remained the same.

4.4.4 Temperature

Temperature variations are not considered in this thesis and all tests were conducted at room temperature. Though a slight increase in temperature was noticed, mainly due to electrical power consumption, no specific effects were analysed and studied.

4.4.5 Grain/Particle Size

These were kept constant throughout the tests. The particle size was different for silica and starch suspensions.

4.5 Preperation of ER Fluids

Two fluids of different compositions were tested for their ER properties and damping characteristics. The silica fluids were prepared as per Winslow Patent No. 3,047,507 [1,9]. The concentrations of different constituents used

were roughly within the ranges prescribed in references [1,9]. The preparation of two fluids are discussed below.

4.5.1 Silica Fluid

Coarse silica was ground into a finely divided powder by planetary milling. Normal tap water was added to the coarse silica and about 4 to 5 ceramic balls were put in the bowl. The bowls were then shut tight and milled for about 8 to 10 hrs., at a speed of about 4 rps. The finely powdered suspended silica in water (semi-solid) was then removed in a pater dish and heated in an oven for about 12 to 14 hrs. at about 70° C. The heating duration was decided by the temperature of the oven but care was taken to save silica from sintering. This dried silica was then again milled (dry) to give a homogeneous fine powder.

The particle size and shape were then analysed through an electron microscope. The silica particle size was in the range from 1 - 5 microns. The shape of the particles were not spherical in nature and were irregular as shown in Photo 4.2. If the particles were found to be of higher grain size, then they were again ground in order to obtain the size within the range.

4.5.1.2 The Fluid

The ground silica was added to the dispersant phase xylene. A small amount of triple distilled water and a surfactant as per the ratios provided in references [1,9] were also added.

The silica fluid which was used had the following percentage weight ratios. For 36% by W/W

Xylene	53% W/W
Water	5.5% W/W
Surfactant	5.5% W/W
Silica	36% W/W

The surfactant used was glycerol mono oleate.

First, xylene was measured as per weight and then water and surfactant were added to it. The solution was stirred with the help of a magnetic stirrer. Silica was then added gradually while the fluid was being stirred to give the required colloidal suspension of silica in xylene.

Another way of preparing the suspension was to first add silica in xylene and then add water. The solution was then stirred thoroughly for some time. Due to the difference in density ratios of silica (heaviest), water (heavier) and xylene (lightest), the silica settles at the bottom in lumps. Surfactant was then added to the solution and then again stirred forming a suspension of silica in xylene. This fluid was then put for planetary milling at lower milling speeds with less number of balls, for 4 to 5 hrs. to form a homogeneous suspension.

The fluid is in the form of a semi-solid paste and generally lacks flowability. As xylene is volatile, some amount of it is always vapourised. Therefore, to impart flowability the required quantity of xylene is again added while using the fluid.

The main point to be noted here (which was observed repeatedly), is that initially this flowable semi-solid paste, resembling any petroleum gel, does not show the ER effect on the application of high fields. But due to continuous shearing and application of high fields, this gel slowly transforms into a liquid state with silica suspended in it. As soon as this change occurs, the ER effect starts to appear. The ohmic resistance of the fluid was measured to be around 200 k ohm.

4.5.2 Starch Suspension

4.5.2.1 Starch as Dispersant

Flour starch was first ground into finely powdered starch by planetary milling. The planetary grinding was done without addition of water or any other fluid, as it may have caused problem while heating the starch in the oven. The powdering can also be done in a normal mixer- grinder to produce

a fine powder. The particle size and shape were then analysed by an electron microscope. The particle size used was in the range from 15 - 25 micron. The shape of the particles were generally spherical as shown in Photo 4.3.

4.5.2.2 The Fluid

The ground starch was then added to the dispersant phase with xylene, small amount of water and the surfactant. After a few trials, (in the absence of any available data), the following composition was used:

Xylene	52% W/W
Water	4% W/W
Surfactant	4% W/W
Starch	40% W/W

Here also the surfactant used was glycerol mono oleate.

First xylene was measured and small amount of water added to it. This was then stirred. The needed quantity of starch was added and again stirred using a magnetic stirrer, and lastly the surfactant was added in order to attain the needed suspension of starch in the fluid.

Unlike the previous fluid, this fluid was readily usable and showed immediate effects. The ohmic resistance of this was measured to be around 400 k ohm.

4.6 FAILURES

In the initial stages, while fabricating the model, the electrode gap (gap between cylinder and the piston) was machined to 0.2 mm as only low voltage DC supplies were available. The continuity of the model was tested at resonance for any signs of contact while in operation (using a multimeter). Many problems arose and occasionally, the continuity did occur at resonance frequencies. Thus, the modification of the piston was done as an oversized teflon washer. This gave problems of unnecessary coulomb damping arising due to its rubbing with the cylinder walls. This was then machined to very fine clearances of 0.1 mm (gap between washer and cylinder) which is still

maintained.

Initially, the first batch of fluid was prepared by using silica gel [20-45 micron] also commercially named as Cellite, in combination with kerosene, water and soap solution. The solution was a thick paste and the water initially used was normal tap water which affected the purity of the fluid. This fluid when used caused an instant breakdown and heavy current flow. The reasons attributed to this were the low purity of the fluid and the small electrode gap maintained with such coarse silica gel size (coarse for the gap 0.2 mm).

Successive attempts for making a fluid with this combination failed and the gap was increased to 0.8 mm. Fluids with silicon oil also failed to respond because the viscosity of this oil was very high.

Subsequently, silica suspensions were made which proved to be effective.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter deals with the experimental observations which are recorded as transmissibility curves to analyse the damping characteristics of the ER fluid and the Electro-Rheological vibration damper as a whole. The parameters considered for the experimental analysis, are the field strength, silica concentration, shear rates, feasibility of AC or DC fields and the variation of the constituent percentages. The effect of these parameters on the apparent variation of the viscosity, as a direct variation on the transmissibility have been analysed through the transmissibility curves. The effect of the changes of certain parameters on the electrical and the rheological properties have also been analysed. A brief effort has also been made to correlate these effects with those discussed in Chapter 2.

5.1 Silica Suspended ER Fluid

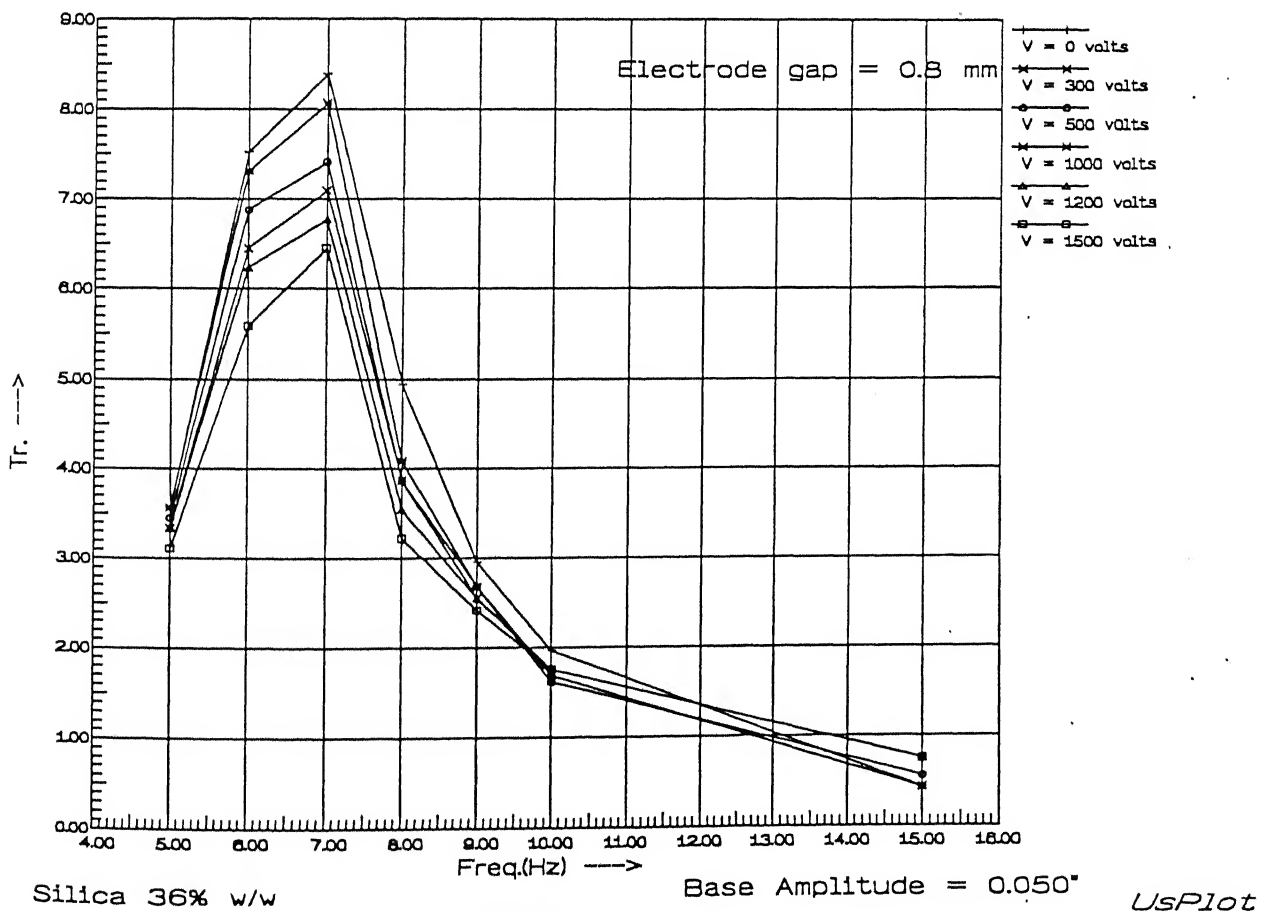
Silica fluids were tested in the test rig (the modelled vibration damper)

and the transmissibility curves are plotted to characterise the change in fluid viscosities on application of electric fields. Each parameter is dealt with separately under different subheadings.

5.1.1 Silica Concentration

Silica suspensions with different silica concentration were tested to analyse the effects on the apparent change in Electroviscosity, through transmissibility curves. The fluid having a 36% W/W silica concentration was first tested at a constant base excitation amplitude of 0.050". An excess wt. of 3.5 kgs was attached on to the top of the loading platform in addition to the weight of the accessories attached to the piston and the spring. The natural frequency was found to be around 7 Hz. We are mostly interested in the transmissibility at the resonance and in the regions $\omega \geq \sqrt{2} \omega_n$.

The transmissibility versus excitation frequency curves are shown in Fig. 5.1-5.6. As evident from Fig. 5.1, as soon as DC fields were increased (field



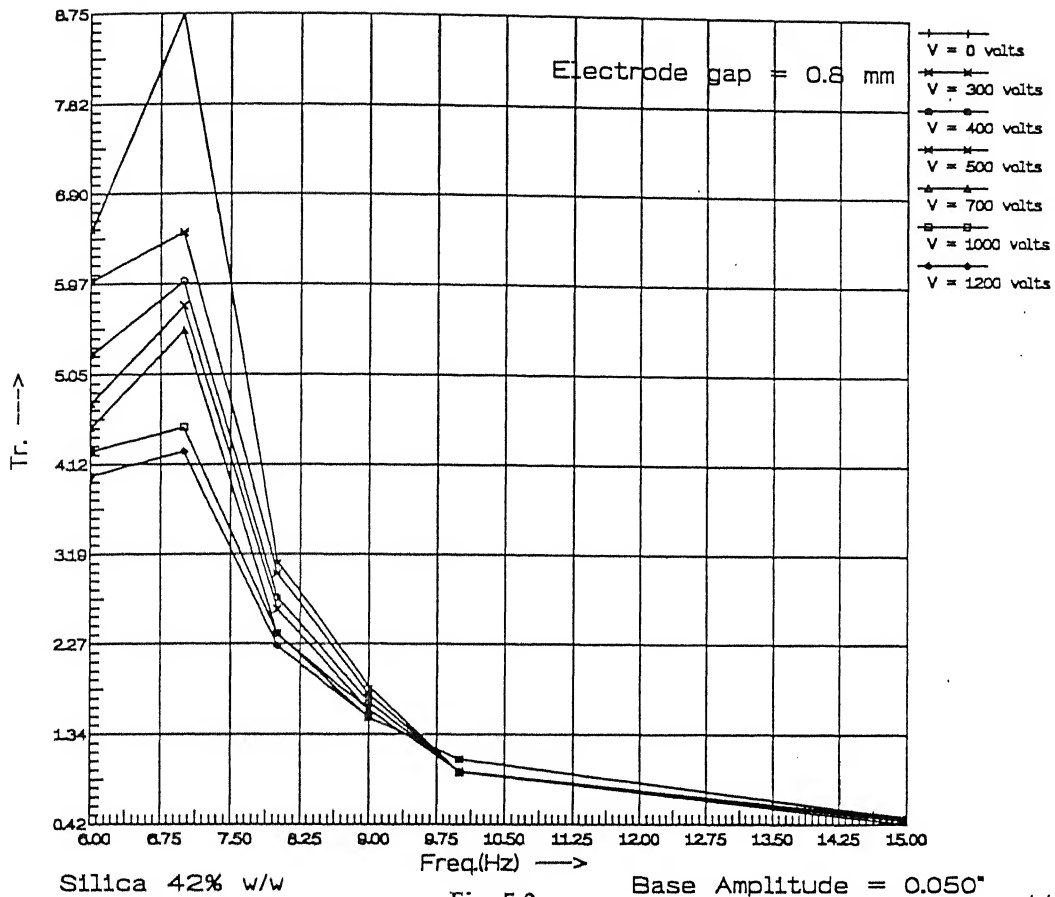


Fig 5.2

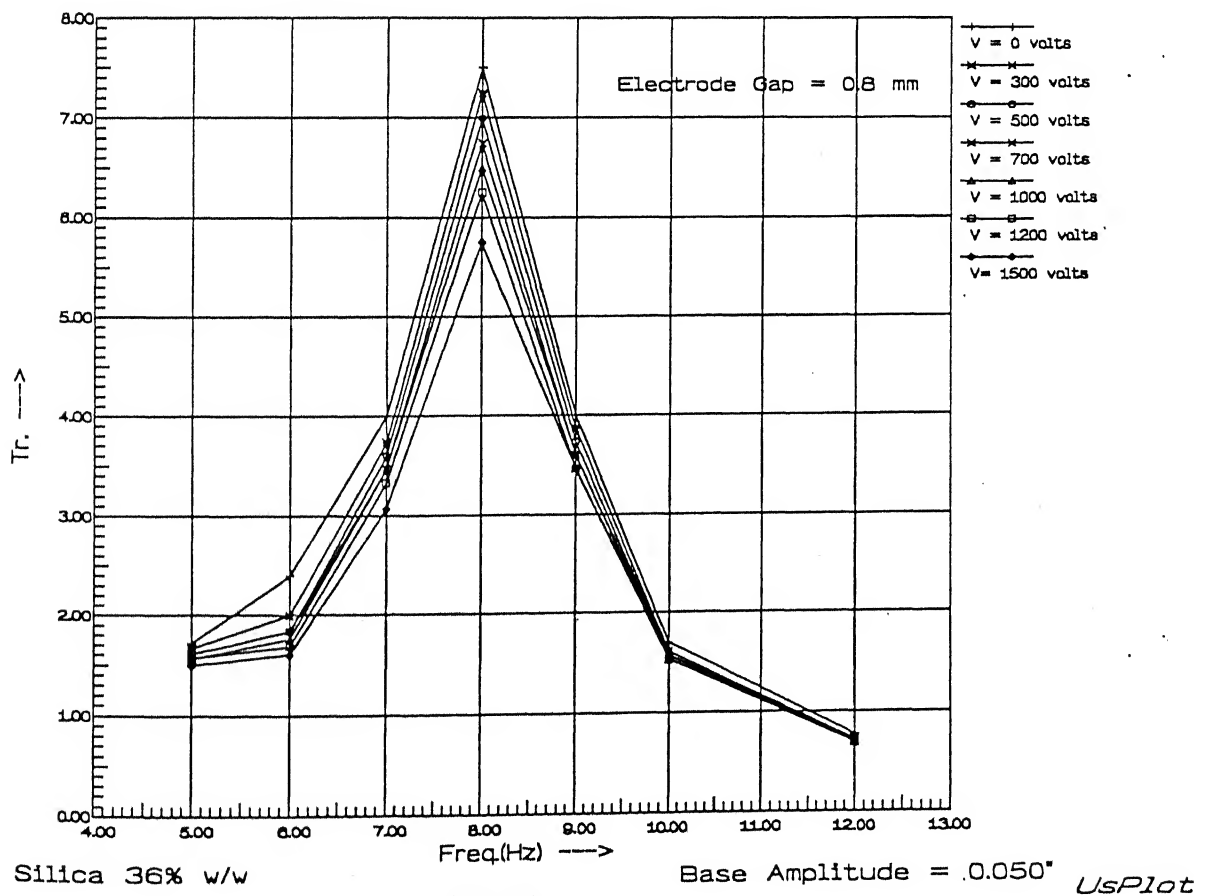


Fig 5.3

$E = V/d$ where, V is the applied voltage and ' d ' is the electrode gap), a significant decrease in the resonance transmissibility occurs. Each curve corresponds to a particular field strength. The field was increased in steps, till appreciable effects in the decrease in the peak to peak amplitude were noticed on the oscilloscope. As seen in Fig 5.1, the decrease in transmissibility, (corresponding to each transmissibility curve) shows the damping characteristic as a function of field. The drop in transmissibility as observed from the curves is around 20% at a high field strength of about 1.875 kV/mm (corresponding to an applied voltage of 1500 volts)

The effects are sustainable and the drop or increase in the transmissibility is not dependent upon time. No change in the fluid characteristics was observed when sustaining the field for longer durations.

At regions beyond $\omega > \sqrt{2} \omega_n$ the transmissibility increases with an increasing field due to increase in the viscosity (damping) of the fluid. This is in accordance with the transmissibility curves. It may be noted that as expected the transmissibility is nearly unity at or around $\omega = \sqrt{2} \omega_n$.

The fields could not be increased further due to the limiting current constraint of the supply, which tripped with any further increase in the voltage.

The silica concentration was increased further to 42% W/W and the experimental procedure repeated, keeping the base displacement set at 0.050" (Fig. 5.2). As evident on comparison with Fig. 5.1, the decrease in the transmissibility is definitely larger than that observed with 36% silica content. Alternately, the increase in electroviscosity was more appreciable with higher silica concentration fluid. A decrease in the transmissibility of around 50% at the maximum field has been obtained. The field could not be increased further due to the current constraints on the supply.

The same tests were repeated by changing the excess mass to 2.5 kgs to have an increased resonance frequency of around 8 Hz and in order to decrease the amplitude of the mass to reduce the shear velocity (which will be dealt with later in this chapter). Consider Figures 5.3 and 5.4. The effect of silica

concentrations is in full agreement to the observations made earlier and also as discussed in Chapter 2. Here the decrease in transmissibility is around 23% with silica concentrations of 36% W/W and a field of 1.875 kV/mm (Fig.5.3). With 42% W/W silica concentration, the decrease in transmissibility at resonance is observed to be of the order of 45% corresponding to a voltage of $v = 1200$ volts (Fig. 5.4). The nature of variation of transmissibility with frequency in all these figures suggest that the damping provided by the fluid is close to viscous in nature.

5.1.2 Observations and Discussions

5.1.2.1 Rheological

(i) Silica concentrations play a very important role in the efficiency of the fluid. With the increase in silica concentrations the effective decrease in transmissibility are larger as compared to the dilute fluids, for about the

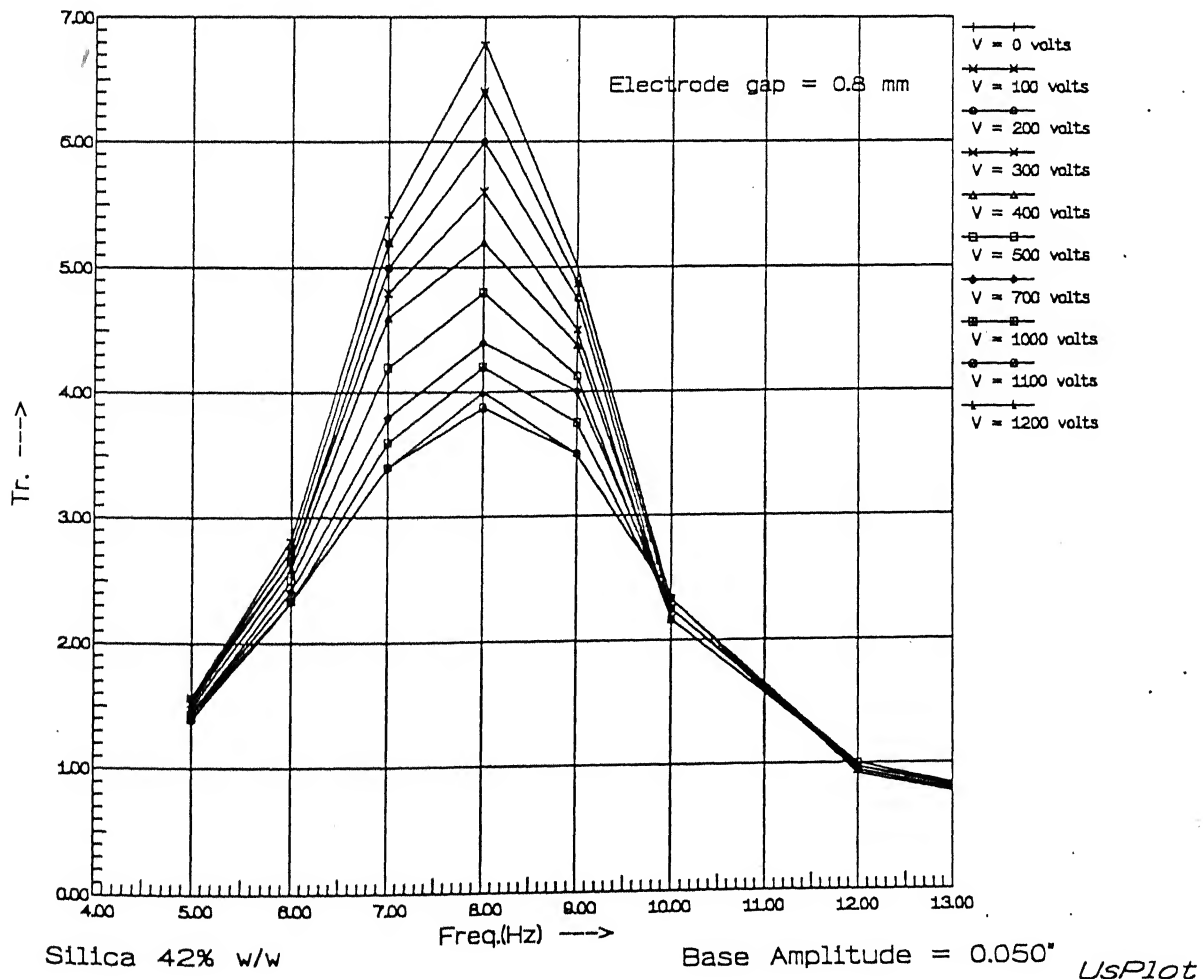


Fig. 5.4

same fields and sometimes even at lower fields.

(ii) With higher concentration of silica, the electro-rheological effects start to appear even with low fields as is evident from Fig 5.2. Alternately, with higher concentration fluids, though field plays an important role, but the concentration predominates this field effect. So we can consider the phenomenon as highly dependent upon the concentration phase. Comparing Figures 5.1 & 5.2 and Figures 5.3 & 5.4, it is evident that the appreciable effects, start to occur even at low field strengths of 125 V/mm in high concentration fluids, whereas in lower concentration fluids, pronounced effects are observed only at higher field strength of around 375 V/mm and above. Therefore, to increase the effectiveness of fluid to show appreciable increase in damping, higher concentration of silica is a better choice (Fig5.5).

Higher the silica concentration, more is the number of ions that are available at the effective surface area. With a dilute fluid, one obviously requires a higher field strength to polarise the same number of ions .

5.1.2.2 Electrical

As electrical variables are the portrait of the ER fluid, these are thus the

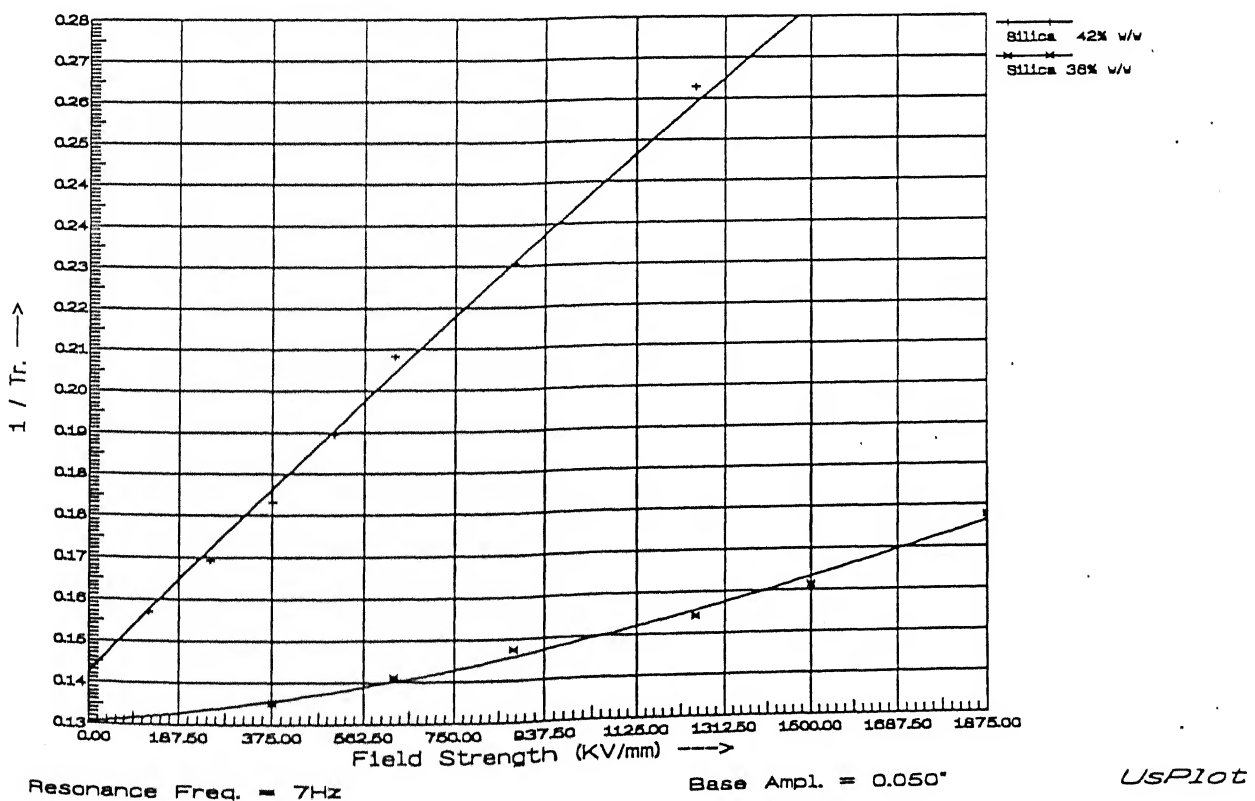


Fig 5.5

first measurable quantities noticed. The following observations are made.

(i) At higher silica concentrations, the effects are pronounced but with an increase in dielectric loss. It is clearly evident from Fig 5.5 that the dilute fluids could sustain high fields (1.875 kV/mm) without showing high conductivity but the higher silica concentration fluids could sustain not more than 1.25 kV/mm after which the supply tripped due to high current conductivity. It was also observed (not plotted here) that with still higher concentration of silica suspensions, though the effects were more pronounced even at fields of 625 v/mm (corresponding to 500 volts), the supply tripped off due to drawing of heavy current.

(ii) The occurrence of the ER effect is symbolised by a sudden variation in transmissibility, on application of the fields (Photo 5.2). It was observed that the effect appears on the onset of the current flow. It is to be noted that, it is actually the effect which causes this current to flow. As the ions get polarised on the application of the field, they align or move towards their respective poles. This phenomenon of induced polarisation causes the current to flow. This phenomenon was observed with all the silica fluids using DC fields as seen in Photo 5.2. With increase in fields the current also increased steadily upto the point where the supply tripped. The reverse phenomenon was observed (but not instantaneously as in the previous case) when the fields were removed suddenly as shown in Photo 5.3 .

The reverse effect is a gradual increase in the transmissibility (or decrease in the damping) and can be attributed to the model (piston and cylinder) behaving as a charged capacitor initially with a dielectric in between. On removal of the voltages, the residual charges take that small time extra for discharging completely. Though, this phenomenon has not been reported, but was observed while working with DC fields on silica suspensions.

(iii) When the silica concentration was increased more and more gradually, to near saturation (about 70%), it was observed that the supply tripped off, at very low applied fields. This is attributed to the shorting of the elec-

trodes (discussed in Chapter 2). This was due to the high charge density and the high dielectric loss. These particles in turn formed a good conductor link between the two electrodes causing the dielectric breakdown (as discussed in Chapter 2) of the fluid.

(iv) One more observation which was made was that at high field strengths and high concentration of silica, the ER effects remained constant. This is discussed in Chapter 2 as high field tail off. This saturation phenomenon can clearly be seen in Fig 5.4.

Surprisingly, the same effect is even observed for dilute solutions of silica (Fig 5.6). The effect or decrease in transmissibility is also not appreciable from $V = 1000$ volts to $V = 1500$ volts compared to that observed from $V = 0$

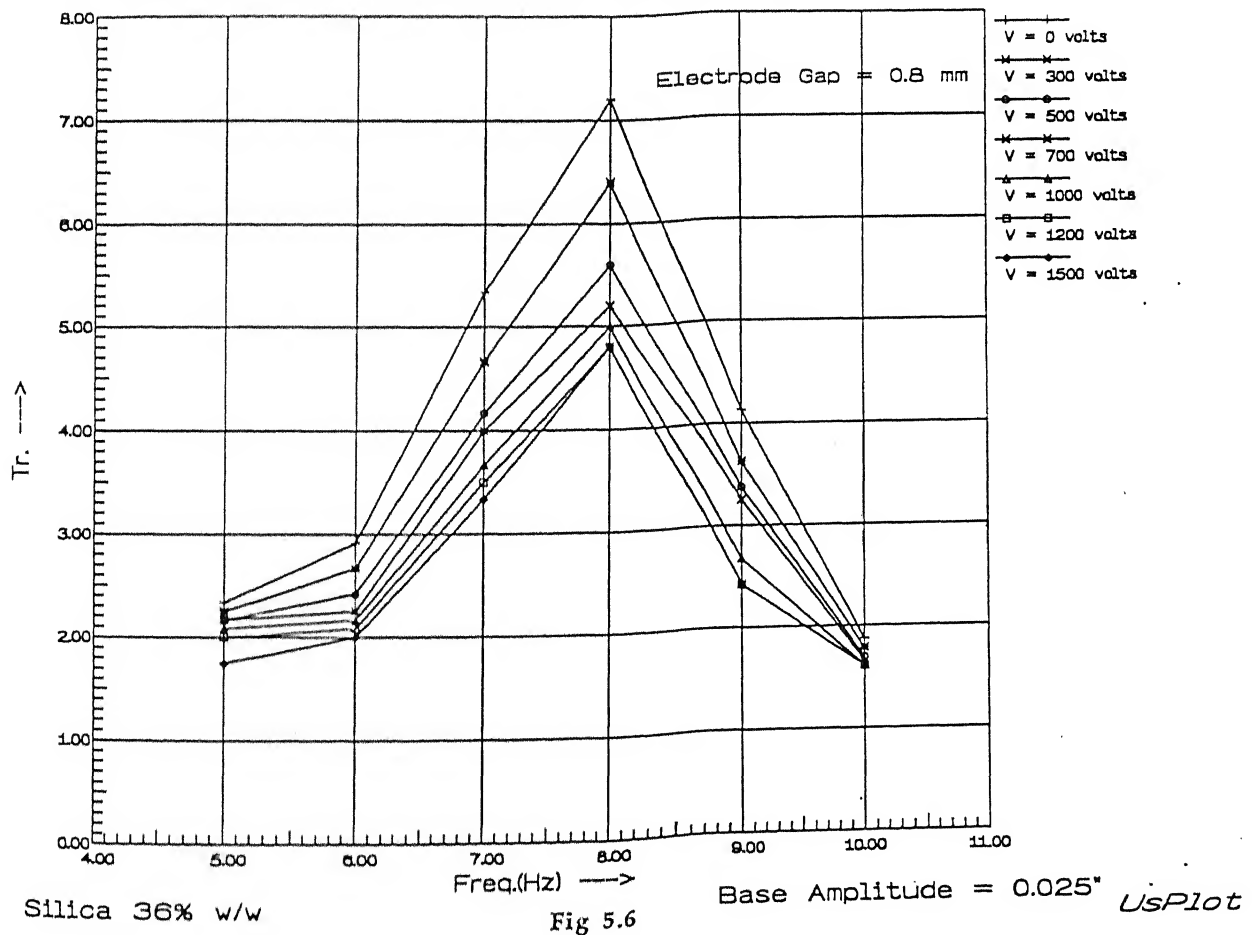


Fig 5.6

to 700 V. This is due to the fact, that the number of polarised ions are less and all the ions have been polarised at low fields, thus causing saturation.

(v) It was observed that initially when the field is switched on, the current shoots up, but then stabilises at some low value. But with this drop

in current the transmissibility also marginally increased to a steady value at that field and current. This phenomenon was not observed on switching at low fields, but was observed at high fields as shown in Photo 5.2 . As a result, a kink near the start of the effect is seen. This reversal phenomenon was gradual at times when a particular field was maintained for longer duration. This was one of the reasons for recording data in the descending order of field strength.

5.1.3 Shear Velocity

The shear velocity also plays a very important role, as discussed previously. To analyse the effects of shear velocity, tests were carried out at high frequency, keeping the base displacement and silica concentration the same. The base amplitude was set constant at 0.050" and silica concentration constant at 42%. Tests were carried out at higher resonant frequency of 12 Hz (without addition of extra weight on top).

This test was done, firstly to assess the frequency dependance and secondly, to analyse the effects on the electroviscosity at high shear rates. Shear velocity is not constant and varies sinusoidally .As there is a relative motion between the cylinder and the piston it gives rise to shear. The shear rate can be calculated as:

Shear Rate at resonance:

$$\text{Cylinder movement} = A_c \cos \omega_n t$$

$$\text{Mass movement} = A_m \cos (\omega_n t - \phi_n)$$

$$= A_m \sin \omega_n t, \text{ as}$$

$$[\phi_n = \tan^{-1} (1/2\xi) \approx \pi/2 \text{ for small } \xi]$$

$$\text{Relative Velocity} = \omega_n (A_m \cos \omega_n t - A_c \sin \omega_n t)$$

$$\text{and Max. rel. vel} = \omega_n \sqrt{(A_m^2 + A_c^2)}$$

$$\text{Max shear rate} = \omega_n \sqrt{(A_m^2 + A_c^2)} / d$$

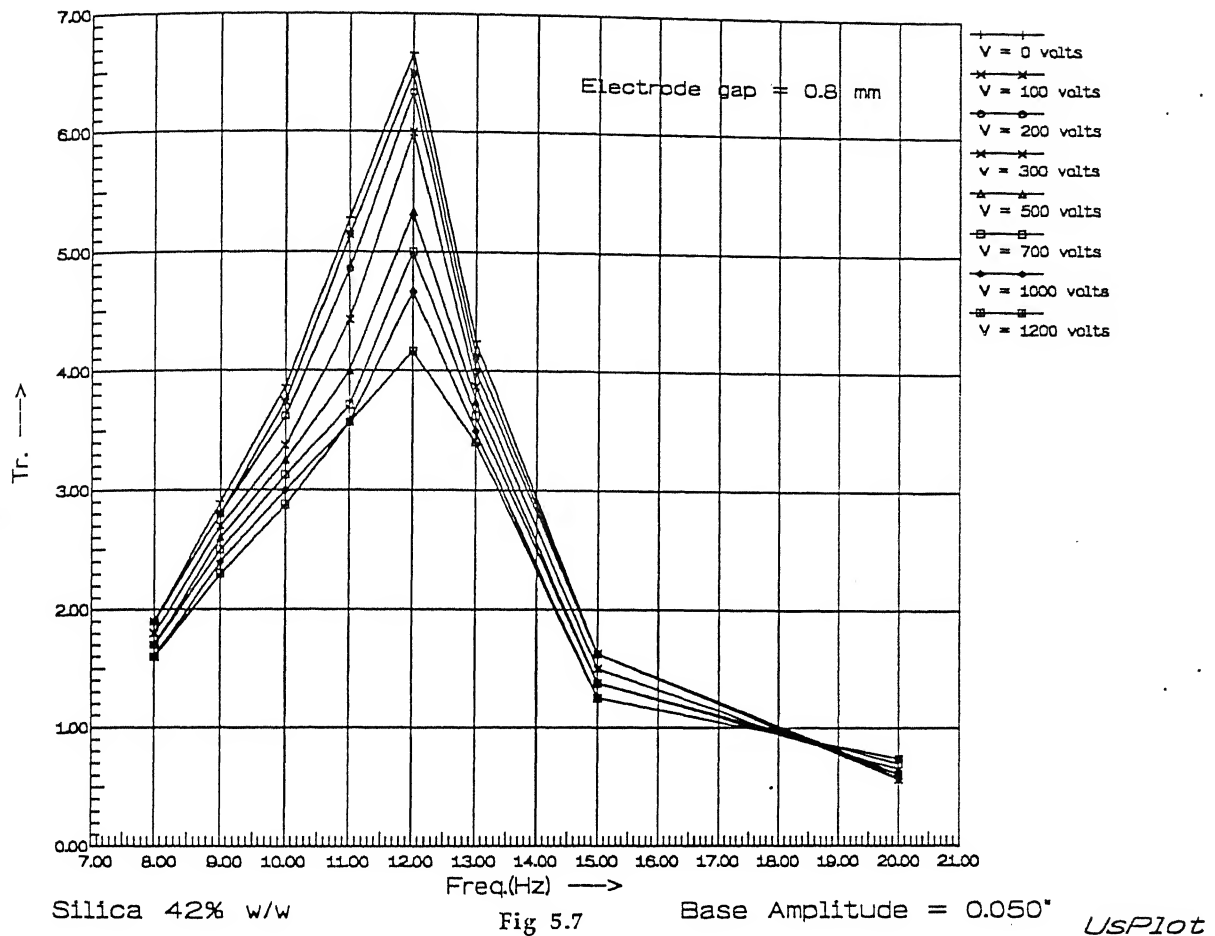
where, A_c = amplitude of the base or the cylinder

A_m = amplitude of the vibrating mass ,

ω_n = natural frequency, and

$d =$ electrode gap

Consider Figs 5.2 and 5.7. The shear rate in the first case would be roughly equal to 614/sec. with a resonance frequency of 7 Hz. In the second



case the shear rate is 810/sec. with a resonance frequency 12 Hz. From these figures it is observed that the higher the maximum shear rate, lower is the decrease in transmissibility. Though the exact nature of the effect of shear rate has not been reported, this observation seconds the report of the effect of shear velocity on electroviscosity (Chapter 2).

The frequency dependance of this phenomenon has also been ruled out, at least within the range of frequency encountered in the present experiments. The decrease in transmissibility at high shear rates is attributed to the high shearing velocities, hindering the complete polarisation of particle and the formation of chains amongst the double layers (Chapter 2).

5.1.4 Constituent Composition

(i) *Silica Concentration*

When dry measured powder silica was added in the fluid (already showing same ER effects) and the field applied, the transmissibility decreased but the effects were seen to be marginal. But when enough time was given before applying the fields, there was a drastic change in the effect. This was due to the fact that water had not been completely adsorbed on the surface to give the double layer phenomenon. Thus, it is a prime requirement for the water to be adsorbed on the particle surface. From the electrical point of view, the addition of silica increased the dielectric constant of the fluid, increasing the dielectric loss and in turn increasing the conductivity on the application of fields. The ohmic resistance of the fluid increased (checked with a multi-meter). But this addition also increased the charge density which is a cause for the higher current flow. The higher silica concentrations also increased the viscosity of the fluid.

(ii) *Xylene*

Pure xylene when added to the fluid decreased the dielectric constant of the fluid and consequently the dielectric loss. Xylene was added to impart flowability to the fluid. As xylene is volatile in nature, it vapourises affecting the fluidity. Thus xylene had to be replenished by small amounts at regular interval.

(iii) *Water*

Water plays a very important role in the electro-rheological effect, especially in silica suspensions. The water used was triple distilled water to lower the conductivity. The water increased the dielectric constant of the fluid and in turn increased the dielectric loss exponentially. On occasions when slight water was added (measured quantity) to polarise the added dry silica, it showed appreciable results. But the current conductivity increased. At higher water contents (greater than 10%), the stage of dielectric - breakdown was

reached showing run away conductance. It was observed that increasing the water contents within prescribed limits always enhanced the phenomenon. But higher water contents caused a sudden breakdown of dielectric strength and a consequent tripping of the supply at even low voltages.

(iv) Surfactants

Though these certainly play a role, yet the effects were not analysed and recorded.

(v) Temperature

A temporary arrangement was made to see the effect of increase and decrease of temperature. A hot air convector was used to increase the temperature of the fluid while in operation. The temperature showed slight changes in viscosity on application of fields, but caused problems of xylene vapourising at very high rates. The conductivity of the fluid also increased appreciably. Due to these reasons the effects were not recorded and analysed.

5.1.5 Problem Areas

There were certain problems faced while using this fluid. These are enumerated below. Some of these can be and have been ironed out, while some of them remain due to the specific nature of the fluid.

(i) Silica will always remain an abrasive solid however finely it may be powdered. Due to continuous movement of piston in the cylinder with finely machined clearances, wear of the piston rod and the rod guide (causing increase in the clearance) was unavoidable.

(ii) Due to the small amount of DC currents flowing, and due to the fact that copper is a soft material, copper in the form of copper oxide is mixed with the fluid. This changed the colour of the fluid and also helped in the coagulation of the silica particles.

(iii) There is a tendency of the suspended particles to coagulate at the bottom of the cylinder when not in use for long periods. The coagulation is quite strong as the particles adhere to each other and have to be scrapped out and remixed to make the fluid reusable.

(iv) As xylene is volatile in nature, measured small amounts of xylene had to be added from time to time to impart flowability.

The first two problems can be ironed out. The setup has already been modified with a lower dia piston rod and a brass bush as a piston guide thus, solving the first problem for the time being. The second problem can be overcome by using a stainless steel cylinder which would be discussed later. It should be noted here that the material used should be hard, workable and resistive to general wear and tear and lastly non-magnetic in nature, which is the main requirement for the set up.

5.1.6 Summary

To summarize, experiments were conducted using the silica fluid of different concentrations and the apparent change in viscosities, on the application of high DC fields, were recorded as transmissibility curves. The silica concentration was the main parameter studied, along with effects of shear rates, field strength and frequency. Increasing silica concentrations increased the electro-viscosity and decreased the transmissibility (Fig. 5.5). However it affects the electrical properties of the fluid with increase in dielectric loss and dielectric constant. More water content increases the electroviscosity, but higher contents of water lead to lowering of dielectric strength leading to an early dielectric breakdown.

The high concentration fluids were also tested under AC fields, the effects were appreciable but due to high conductivity these fluids could not be used further.

5.2 Starch Based Fluid

The starch as dispersed phase in xylene was similarly tested (as the silica fluids), with the only difference that the fields applied were AC. The experimentation methods remained the same except for the parameters considered. The main parameters under scrutiny were the starch concentrations and the shear rate. These parameters would be dealt separately under different sub-headings.

5.2.1 Concentration of Starch

Initially, fluid with starch concentration of 40% W/W was tested in the vibration damper with the application of AC fields of 50 Hz. The base amplitude was set at 0.050" and the natural frequency was changed to 7 Hz by mounting a load of 3.5 kgs on top of the loading platform. Here also we would concentrate on the resonance and high frequency regimes.

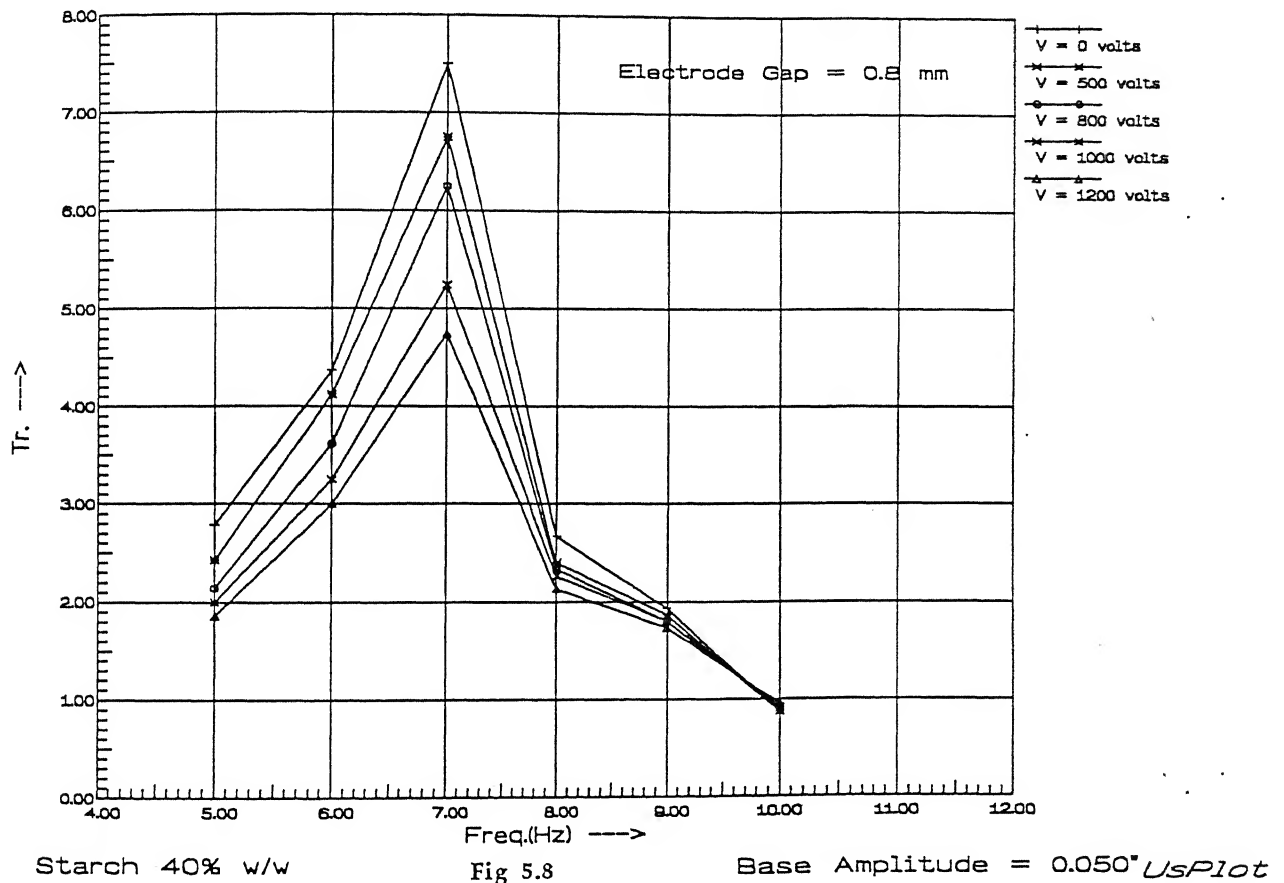
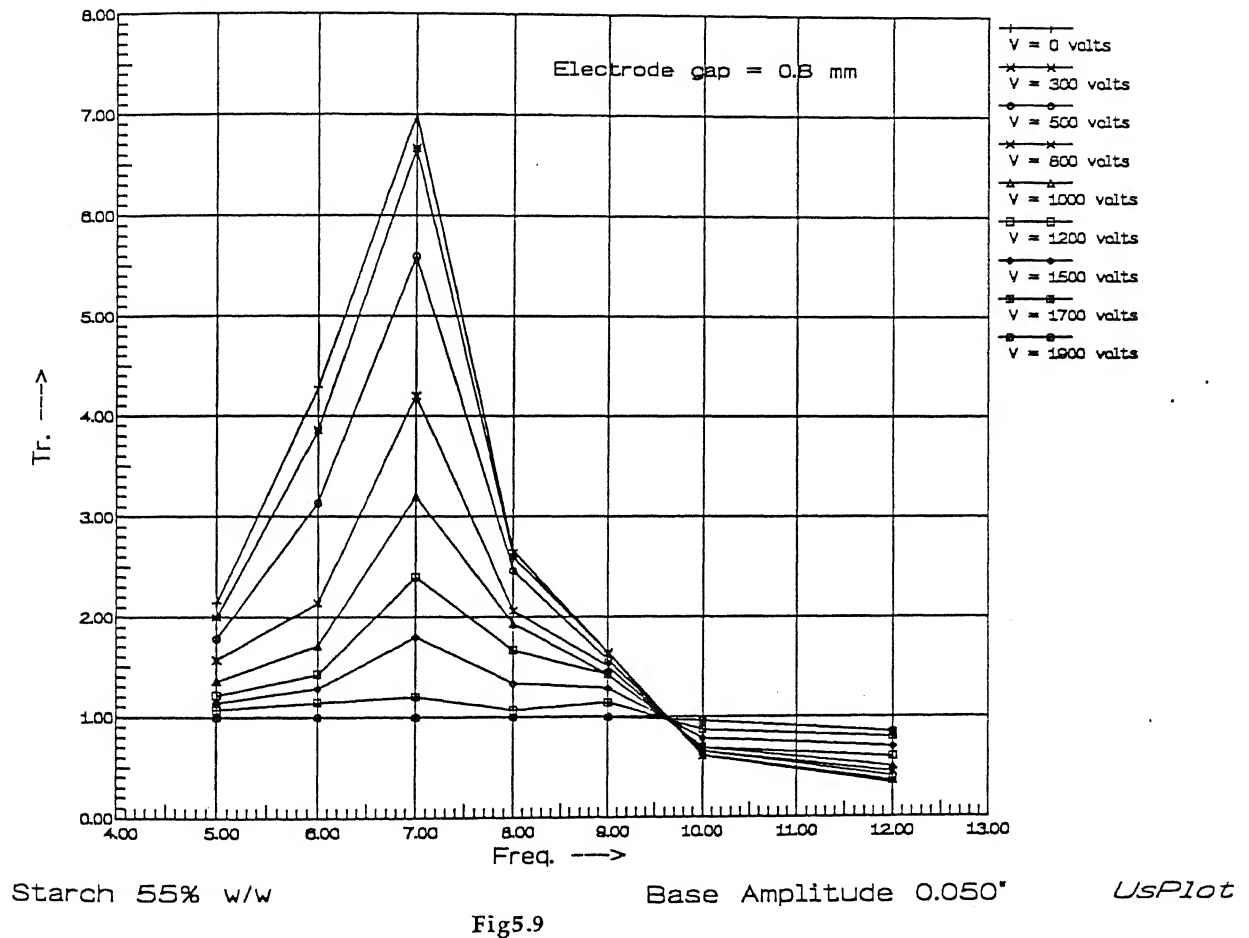


Figure 5.8 shows an apparent increase in the electroviscosity. The field was increased until the stage, where the dielectric loss increased beyond the tripping current of the supply (45 mA). As observed from this figure, the transmissibility decreased around 37% with a voltage $v=1200$ volts. The reverse phenomenon, where the transmissibility increased with the decrease in applied fields was also observed. The fluid obtained its original viscosity at zero field (Photo 5.6).

The effects were also observed to be sustainable and did not alter with time. This shows that the damping characteristics are a function of field.

The effects are also instantaneous and they occur as soon as the field is applied (Refer Chapter 2 and Photo 5.4). The effects on removal of field were also instantaneous unlike, in the silica suspensions working with DC fields (Photos 5.5 & 5.6). This can be attributed to the fact that the (piston and cylinder acting as the capacitor) capacitor is charged and discharged continuously with the changing polarity and no accumulation of polarised ions are there on the electrodes. At regions $\omega > \sqrt{2}\omega_n$ as expected, the transmissibility continuously



increased with increasing fields. The transmissibility was nearly '1' at regions around $\omega = \sqrt{2}\omega_n$.

With fluids having 55% starch concentration the effects were much more pronounced. The effects started to show even at low fields of 375 V/mm. With increase in the field strength, the electroviscosity changed appreciably as seen in Fig 5.9. It can be noticed that the electroviscosity effects are higher at field strength of 1.5 kV/mm (corresponding to voltage $V = 1200$ volts) as

compared to lower concentration fluid at the same field. The transmissibility dropped by about 65% as compared to 37% with lower concentration starch solution.

The effect of starch concentration as observed from the transmissibility curves in Figs 5.8, 5.9, & 5.10 are also in full agreement to the reportings and discussions in Chapter 2. As observed in Fig 5.9, substantial effects start to appear even at low fields. This phenomenon also occurs due to the same fact, that there is an increase in the number of polarised ions which help in forming more interactive double layer bondings (Chapter 2).

5.2.2 Critical Damping

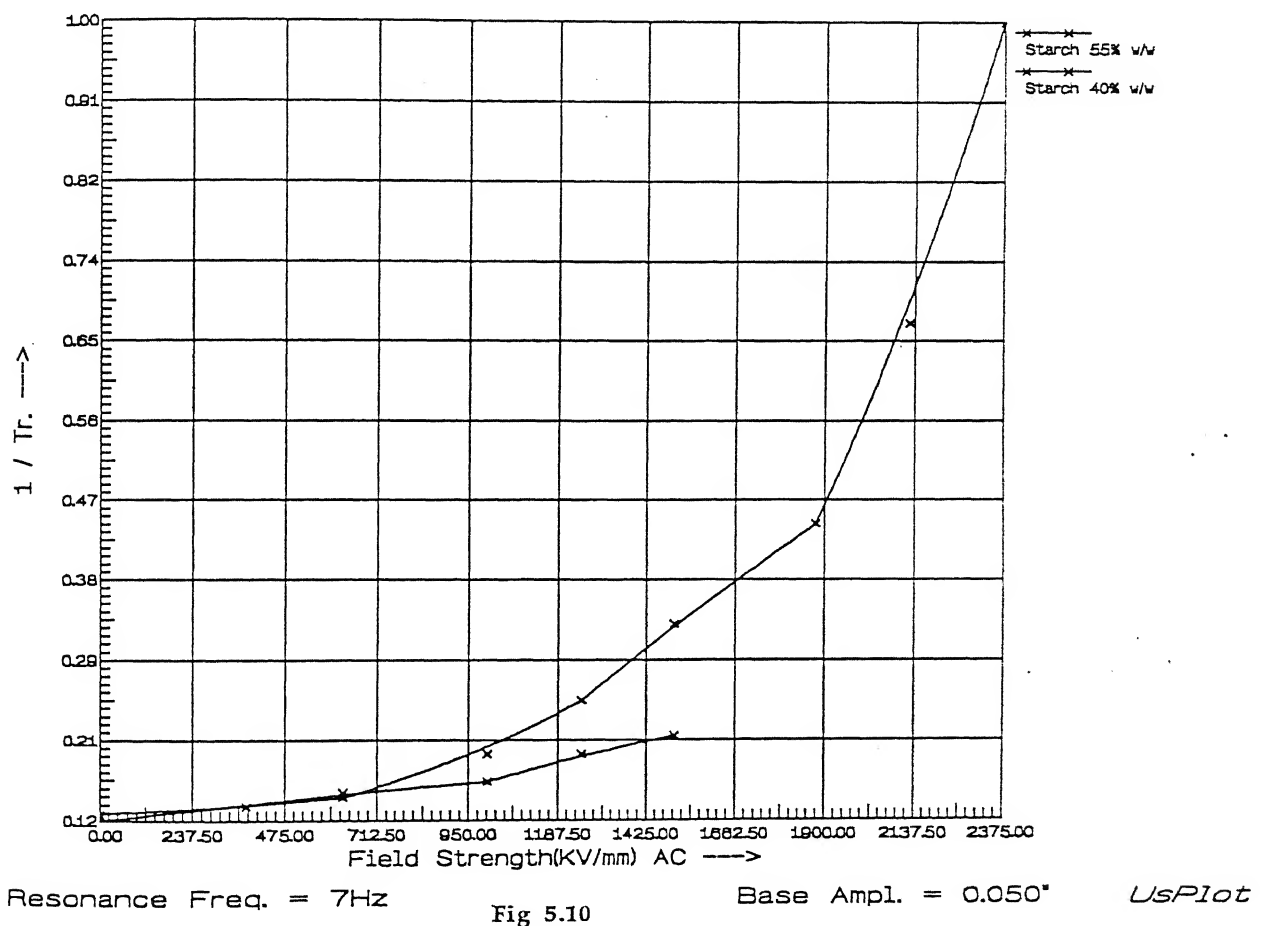
Electroviscosity is a combination of coulomb damping and viscous damping. At a lower field, the viscous damping predominates the coulomb damping. With increasing field, coulomb damping starts to get pronounced till a stage of solidification of this fluid occurs [8]. This stage is termed as the critical damping, where the transmissibility is unity.

This landmark event occurred (Fig 5.9) while using the higher concentration starch fluid (55% W/W). As the fields were increased gradually, increase in the electroviscosity resulted in decrease in the transmissibility. With still increasing field, the transmissibility dropped further to a point where the base amplitude equalled the top mass amplitude, attaining the condition of critical damping or solidification. The solidification effect was achieved at a very high field strength of 2.375 kV/mm corresponding to a voltage, $V = 1900$ volts.

This change in the state of the fluid is observed on the oscilloscope as a change in the velocity profile. The charge amplifier was switched to the velocity range and the magnification adjusted as per the need. As the fields were increased, the velocity amplitude started to decrease until about field strengths of 1.500 kV/mm (corresponding to voltage $V = 1200$ volts), small kinks started to appear at the peaks. These kinks or overlaps indicate the onset of non-linearity i.e, the beginning of the process of solidification. Still

increasing the fields, the amplitudes kept on decreasing with the kinks becoming more prominent at the peaks. Finally, the top peaks started to tilt confirming the non-linearity. These effects are clearly seen in Photo 5.7 .

The transmissibility remains at unity till the break - loose frequency ($\approx \sqrt{2}\omega_n$) is reached. Upto this value of frequency, the damper acts as a rigid connection. In other words, the coulomb friction force remains greater than the maximum inertia force of the top mass.



5.2.3 Observations and Discussions

5.2.3.1 Rheological

(i) The increase in electroviscosity, confirmed as the characteristic decrease in the transmissibility, varies with the field strengths (Fig. 5.10). At very high field strengths, it even leads to a stage of coulomb damping where $Tr = 1$.

This stage is also termed as the solidification stage, where the electroviscosity becomes infinity [5].

(ii) The concentration of the dispersed phase plays a very important role. The higher concentration fluid showed a comparatively higher increase in electroviscosity compared to the lower concentration fluids (Fig 5.10). Also, as observed in Figs 5.8 and 5.9, the effects start to appear even at very low field strengths for higher concentration starch fluids as compared to the lower concentration fluid. Also as discussed in Chapter 2, this increase in electroviscosity with increase in concentration can be attributed to the increased number of polarised ions. Alternatively, more and more ions get polarised to form interactive chains at even low fields. This proves that in addition to electroviscosity being field dependent phenomenon, it is also largely dependent on the concentration of starch.

(iii) The observed phenomenon is not time dependent as the measured transmissibility remains constant during the application of the particular field.

(iv) The phenomenon is instantaneous and it occurs as soon as the field is applied. With increasing the field, the electroviscosity increases with an instantaneous decrease in the transmissibility (at regions near resonance). For regions where $\omega > \sqrt{2}\omega_n$, the transmissibility increases instantaneously with the application of field. On decreasing the field, the effect is also instantaneous with a consequent increase in transmissibility. This can be attributed to the non-accumulation of charge on the electrodes, (due to the fluctuating nature of AC field). Photos 5.4 and 5.6 show the quick response of the fluid to a sudden increase in voltage and vice versa, respectively.

(v) At very high fields causing near solidification, the top mass oscillations are not restricted to harmonic oscillations. They start becoming non-harmonic in nature showing unevenness in the higher or lower peaks and even distortion in the progression of the wave. It was observed on several instances that as soon as the field was decreased, the oscillations restored

back to being harmonic in nature with no distortion observed on the oscilloscope. This was repeated several times to confirm to the effect. Thus while collecting data, the field was increased very gradually.

(vi) The velocity profile showed the same effects as above with small overlap or kinks forming at the peaks, at high fields. With still higher fields the distortion in wave progression were observed along with the change to a non-harmonic wave. It was also observed that the top peaks started to tilt at very high field confirming the non-linearity and also the predominance of the coulomb damping factor in the electroviscosity as seen in Photo 5.7.

5.2.3.2 Electrical

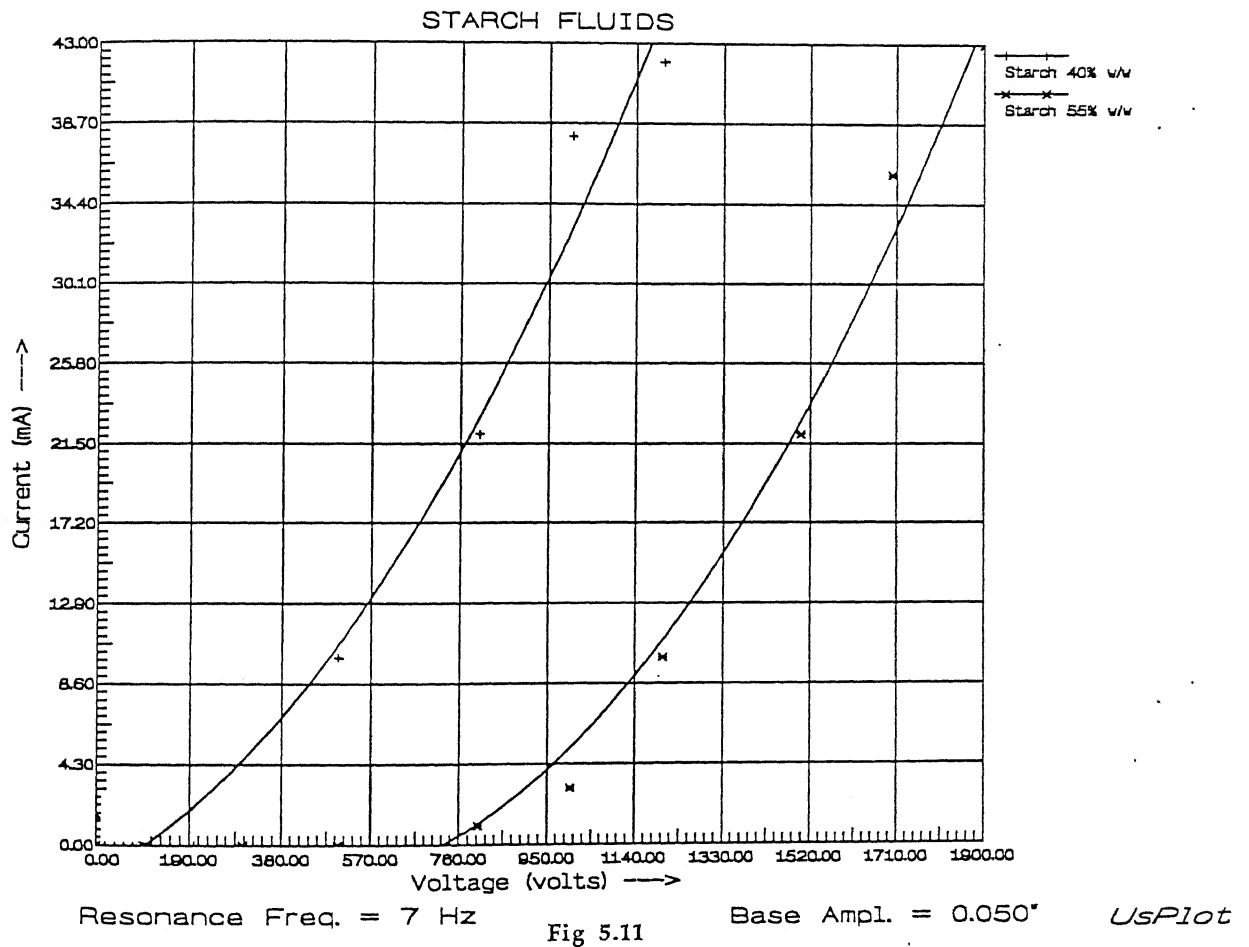
(1) The effective decrease in the transmissibility occurred as soon as the field was applied. However, in the silica suspension with application of DC fields the effect (or decrease in transmissibility) was observed only at the onset of current flow. With starch suspensions, no current flow was recorded on the application of the field, and the decrease in transmissibility was instantaneous. With the increase in the field strengths, no current was recorded until upto a field strengths of 1.5 kv/mm, when a small amount of current (of the order of 8 mA) was recorded (Fig 5.11). Thereafter, the currents increased dramatically with increase in fields, ultimately tripping the supply unit (which has a current rating of 45 mA) at very high fields. This shows a runaway conductance or dielectric breakdown.

It is also worth mentioning that in the lower concentration starch suspension, the applied steady fields achieved were just 1.5 kV/mm (corresponding to voltage $v = 1200$ volts), with not much decrease in the transmissibility (Fig 5.8). The supply unit tripped off immediately, and further increase in the applied voltage was not possible.

(ii) In the silica fluids, increasing the silica concentrations increased the dielectric constant and the dielectric loss restricting the application of higher fields. The effect was just opposite with an increase in starch concentration from 40% to 55%. The dielectric losses were negligible at low fields compared

to the low concentration fluid (Fig 5.11). Rather, the currents started to flow only at high voltages from about $v = 1000$ V and above, which was not the case with the 40% starch concentration fluid, where the supply tripped off abruptly at field strengths of 1.5 kV/mm corresponding to 1200 volts.

(iii) With the 40% starch concentration fluid, it was frequently observed that with any slight steady increase in currents at constant applied voltage or



field (high fields) the applied voltage started to drop steadily and the current continued to increase. This was unlike what was observed in the silica fluids with DC fields. This phenomenon can be explained as follows.

In the first case, as voltage is inversely proportional to the current, so with the steady increase in the current, there is a steady drop in the effective voltage. As the phenomenon depends largely on the applied field, this decrease in the applied voltage decreases the field strength and in turn results in a loss of electroviscosity. In the second case(using DC fields) the current flow is

the measure of the extent of polarisation and therefore, is an after effect of the phenomenon(Chapter 2). The decrease in the current signifies a drop in the number of charged ions and a loss in polarisation, leading to a loss in electroviscosity. This loss in electroviscosity (in both the cases) manifests in the increase of transmissibility.

5.2.3.3 Shear Velocity and Exciting Frequency

To check for any frequency dependance of the phenomenon with AC fields, and the effects of shear velocity, tests were conducted at high resonant frequency at 12 Hz. The base amplitude was set at 0.050".

Tests were conducted with both sets of starch fluids one with 40% starch concentration and the other with 55% starch concentration. Both the tests were done keeping the base amplitude constant at 0.050" with no excess weight on top of the loading platform, restricting the wt. on the piston to be 2.25 kgs. Refer to Figs 5.12 & 5.13, it is clearly evident that there is an appreciable

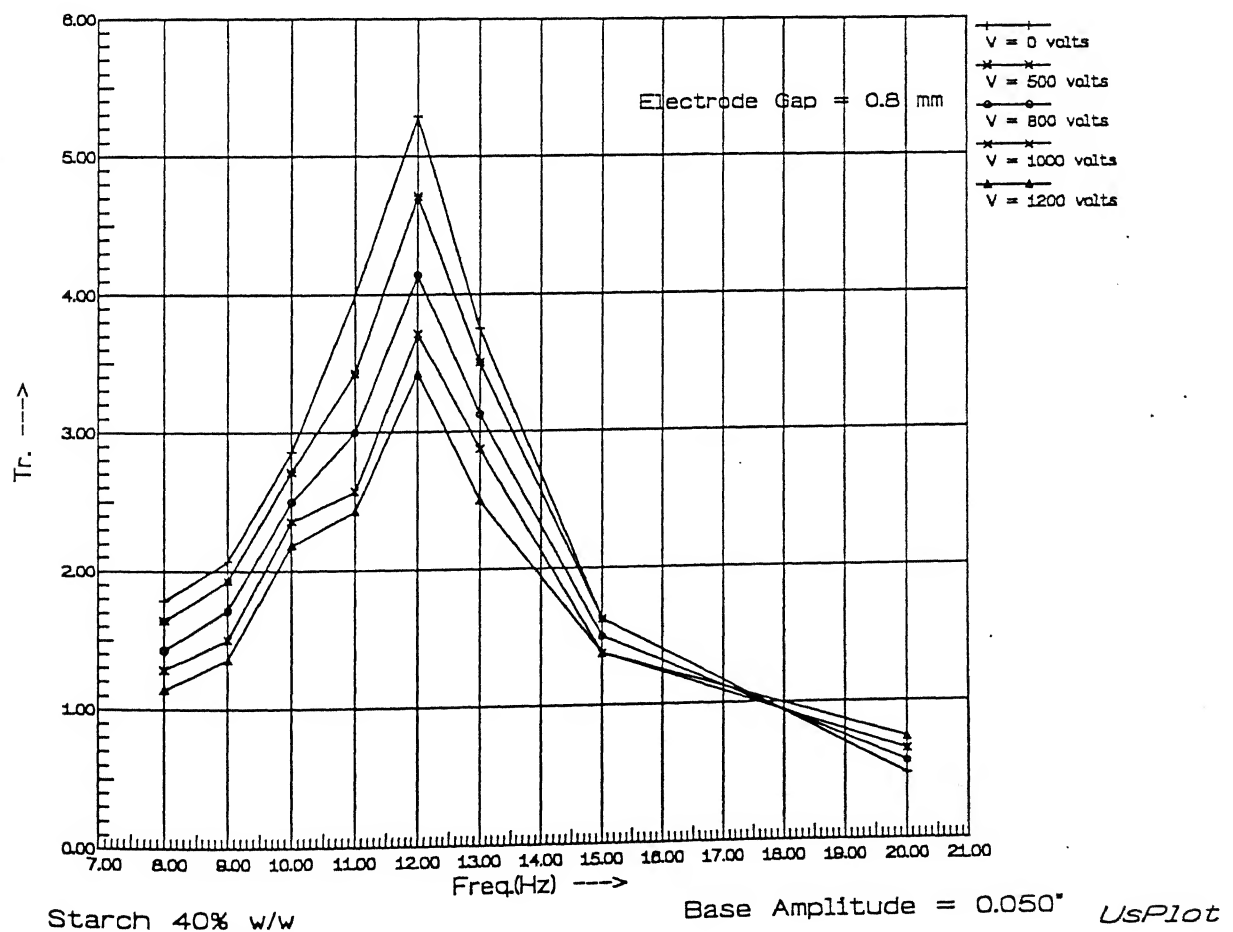
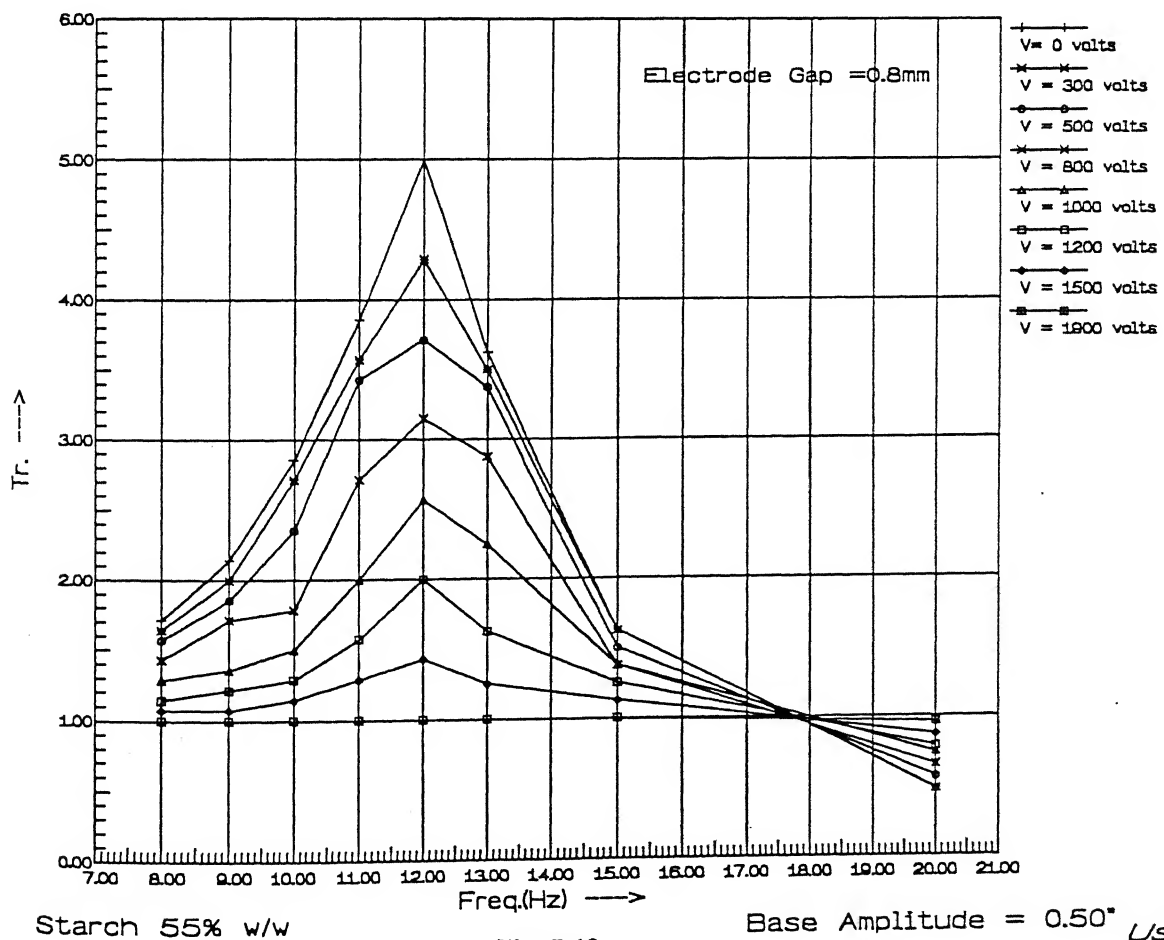


Fig 5.12

drop in the transmissibility with the increase in the field strengths. These figures characterise, that the phenomenon is not frequency dependent and occurs even at high frequency. The figures also confirm the effect of starch concentration on the transmissibility. The higher concentration fluid shows a 60% drop in the transmissibility (Fig 5.13), whereas, the lower concentration fluid (40% starch) shows only a drop of 35%, at field strengths of 1.5 KV/mm corresponding to a voltage of 1200 volts.

The shear rate is not a constant parameter and keeps on varying sinusoidally with the piston vibrations. The maximum shear rate (as already calculated in case of silica fluids) calculated at the resonant peak is about 610/sec. for the model resonating at 12 Hz (Refer Fig 5.13) and about 493/sec for the model vibrating at 7 Hz (Refer Fig 5.9) for the same starch concentrations of 55% . It is clearly evident from Fig 5.13 that the shear rate does not have any effect on the electroviscous phenomenon.



All these effects were noted using AC fields of frequency 50 Hz. Though, reports are there (Refer Chapter 2) that this phenomenon is also frequency dependent (frequency of applied AC fields) but, it has not been covered in this thesis.

5.2.3.4 Critical Damping

The critical damping stage with 55% starch concentration was reached irrespective of the model's natural frequency. Similar, effects were also observed at low frequency excitation at very high fields. The velocity profile showed the non-linearity in the damping. This phenomenon was repeated several times with increasing and decreasing fields. It was also observed that as soon as the fields were reduced to zero, the non-linearity disappeared, showing the transformation from the solidification state back to the original fluid state. In the higher frequency zone ($\omega > \sqrt{2} \omega_n$) the effects fully supported the transmissibility curves, with an increase in transmissibility with the increase in fields (Figs 5.12 & 5.13).

The shear rate (Figs 5.9 and 5.13) (with the same concentration starch (55%)) shows no effect on the percentage reduction in the transmissibility and thus on the electroviscosity. Also observed, that the dielectric losses were similar at different shear rates, with the dielectric breakdown occurring above $V = 2000$ Volts.

5.2.3.5 Constituent Compositions

(i) Starch

Dry starch already has a surface charge or double layer due to the adsorbed moisture on its surface. This was observed during electron microscopy to assess the particle size. The starch particles moved randomly on the impingement of the electron beam, proving that the starch particles have a surface charge. On addition of more starch to the fluid it was observed that the dielectric constant decreased, further decreasing the dielectric loss and consequently increasing the dielectric strength. As also evident from the transmissibility plots for low concentration and high concentration fluids, the

high concentration fluids could withstand high field strength whereas the low concentration fluids showed high conductivity at minimal fields of 1.5 kV/mm (Figs 5.10 & 5.11)

A point to be noted here is that, with the increase in starch concentration, unlike in the case of silica suspensions, where the conductivity increased with the increase in silica concentration, the conductivity decreased appreciably on addition of more starch. This allowed the high concentration starch suspension to sustain much higher field strength. But this increase in the starch concentration should have also increased the conductivity (as the number of polarised ions are increased ,Chapter 2) which was not observed .

(ii) Water

Water is added to the fluid to help in formation of double layers in addition to imparting fluidity. The water content decreases the di-electric strength of the fluid ,increasing the di-electric constant and the loss . As was observed that on adding more starch to the low concentration fluid, the dielectric loss decreased appreciably with an appreciable increase in the di-electric strength. Thus the water content could be one of the factors for the early breakdown of the low concentration (40%) fluid.

(iii) Xylene

As also observed with silica suspensions in xylene, the addition of xylene (used for increasing fluidity) also indirectly increased the dielectric strength of the fluid.

5.2.4 Advantages and Disadvantages of Using Starch Over Silica

5.2.4.1 Advantages

(i) Starch, being not abrasive as silica, is better to work with. It does not cause heavy wear and tear affecting the clearances and it can be easily powdered.

(ii) Starch particles already have a charged layer on the surface due to the adsorbed water. This fluid, unlike the silica fluids, took no time to show the electro-rheological effects.

(iii) Starch fluids are less aqueous than the silica fluids and thus show low conductivity even at high AC fields. They should also be expected to show low conductivity with DC fields. Due to low current conductivity the power consumption is also low.

(iv) Starch is non-toxic, non-abrasive and eco-friendly, whereas powdered silica is believed to cause silicosis, which affects the lungs apart from being non-abrasive.

5.2.8.2 Disadvantages

(i) The biggest disadvantage which could be thought off is the effect of high temperatures. The silica fluids can withstand high temperatures compared to the starch, which would lose its property at high temperatures.

5.3 Summary

Tests were carried out on the starch and silica suspensions in xylene with grain sizes varying in ranges from 15-25 microns and 1-5 microns, respectively. The oleaginous vehicle and the surfactants used were the same. DC fields were applied to the silica dispersions AC fields were used for starch suspensions. In both these cases, it was observed that the dispersed phase concentration played the major role, with a higher percentage reduction in transmissibility, or better damping characteristics with a higher concentration fluid. High water content decreases the dielectric strength of the fluid with an increase in the dielectric constant and loss. Though water (Chapter 2) is a definite necessity for silica suspensions, it should be strictly maintained within the prescribed limits. Addition of the base fluid xylene increases the dielectric strength imparting fluidity.

The phenomenon of electroviscosity was observed to be reversible in nature. With a decrease in electric fields the transmissibility was observed to increase with a decrease in electroviscosity. The variation of electroviscosity with

variation in field was noted to be instantaneous. Though in DC fields the effects occurred only at the onset of current flow, in AC fields no such effect was observed. The effects were observed at the instance of application of the field, with no current flow.

On the application of high field, the stage of critical damping was reached with high concentration starch suspension. The transmissibility in the resonant region dropped to unity.

CHAPTER 6

CONCLUSION

Experiments were conducted using "Electro-Rheological Fluids" as the variable damping elements in a conventionally used [piston-dashpot] vibration damper assembly, designed and fabricated using the shear mode principle.

Experiments were conducted with two kinds of fluids- silica and starch as the dispersed phases, in order to analyse the variation in the damping characteristics (as transmissibility curves) on the application of electric fields. Silica and starch fluids were prepared after analysing the constraints [Chapter 2], and on the basis of the patent available . It is evident from the experiments carried out that the electroviscous phenomenon observed is more or less the same, irrespective of the kind of field (AC/DC) used.

The important conclusions are listed below:

(i) Effect of Dispersed Phase: The results have shown that there is a marked increase in the electroviscosity and in turn a decrease in the resonance transmissibility with increasing dispersed phase concentration..It has been observed that the lower concentration fluids need higher field strength to show the effect, as compared to the higher concentration fluids which operate very effectively at even lower field strengths. In case of silica fluids, the increase in the dispersed phase increased the conductivity and the permittivity with a loss in the dielectric strength. Starch fluids showed a different effect. The conductivity of the fluid decreased appreciably with the increase in the starch concentration. On the application of very high fields the critical damping state was reached. This showed the transformation of the liquid from the liquid to a solid state, on the application of very high field strength. The induction of this non- linear term was observed as a tilt in the peak of the velocity profile. This phenomenon, thus also proves the viability of the prototype model which has viscous as well as coulomb damping.

The feasibility of using ER fluids in the conventional piston cylinder assembly to act as a semi -active vibration damper has been demonstrated.

(ii) Effect of Field Strength: The transmissibility decreases (corresponding to the increase in the electroviscosity) with an increase in the electric field. The decrease was observed to be as a second power of the increase in the field strengths.

(iii) Effect of Shear Rate: The results show that the shear rate did not effect the electroviscosity in case of starch fluids. The transmissibility dropped to unity (stage of critical damping) even at higher operating shear rates on the applications of the fields.

(iv) The feasibility of using either DC or AC fields has been authenticated. Both the fields showed more or less similar results.

(v) The DC fields showed conductivity on the application of the fields implying that the current flow is a must for the phenomenon to occur. With

the AC fields current is no criteria for the occurrence of the effect.

6.2 Future Scope of Work

The model has worked effectively and efficiently to quantify the effects of certain parameters on the damping characteristics (as transmissibility curves). It is suggested that the damping characteristic may be analysed for the effect of certain other parameters listed below.

Chemical

- (1) Temperature
- (2) Particle Size
- (3) Magnetic Colloids
- (4) Addition of Surfactants

Mechanical

- (1) Effect of Impact loading
- (2) Non-harmonic excitation
- (3) Shock
- (4) Effect of high shear velocity

There are certain modifications which can be suggested for a more effective and efficient model. The materials used here are copper and brass. These are softer materials and thus prone to wear and tear. It is suggested to design the damper using stainless steel due to its inherent property of being hard, non corrosive and non-magnetic in nature. The guide bush has been a major cause of concern; it is suggested to use vertical bearings, boxed up in a bearing housing to safeguard it against ceasing and deterioration. The piston rod can also be made of stainless steel with its outer surface hardened and ground to a smooth finish. The surface area can be increased by fabricating the piston and dashpot assembly as shearing concentric cylinders to enhance the effective area of shear.

Finally , attempts can be made to use this damper as an active one ,wherein the response should control the on and off switching of the applied field.

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PHOTOGRAPHS

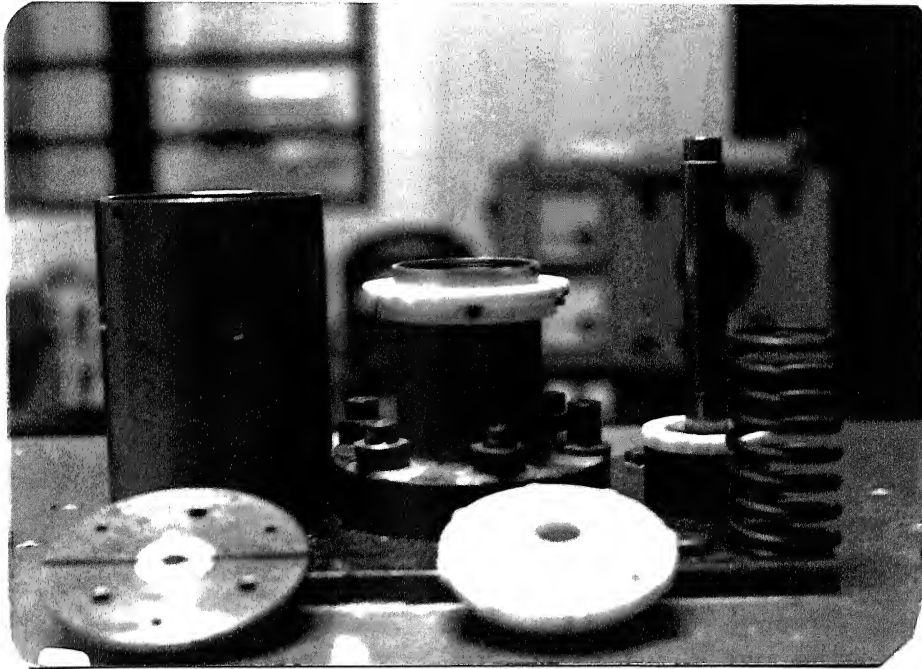


PHOTO 3.1

Parts Of the Vibration Damper



PHOTO 3.2

*The Working
Model*



PHOTO 4.1
Experimental Setup

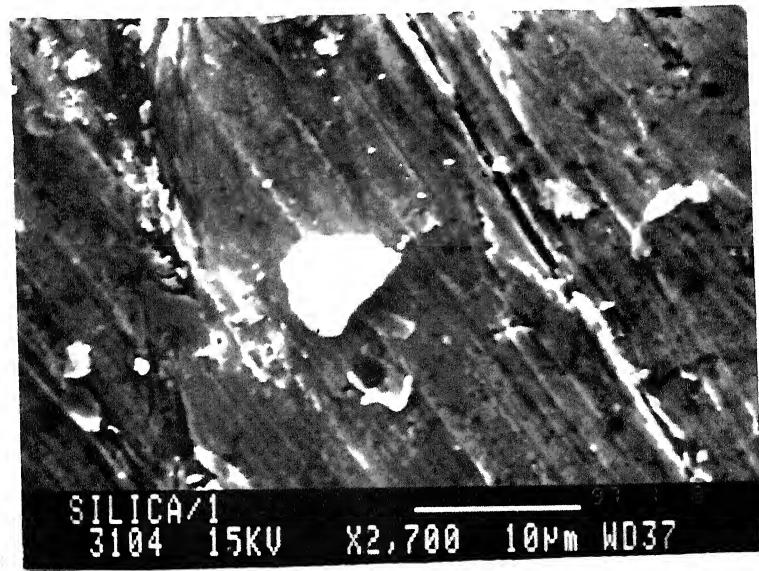


PHOTO 4.2
Silica Particle (1-5 micron)

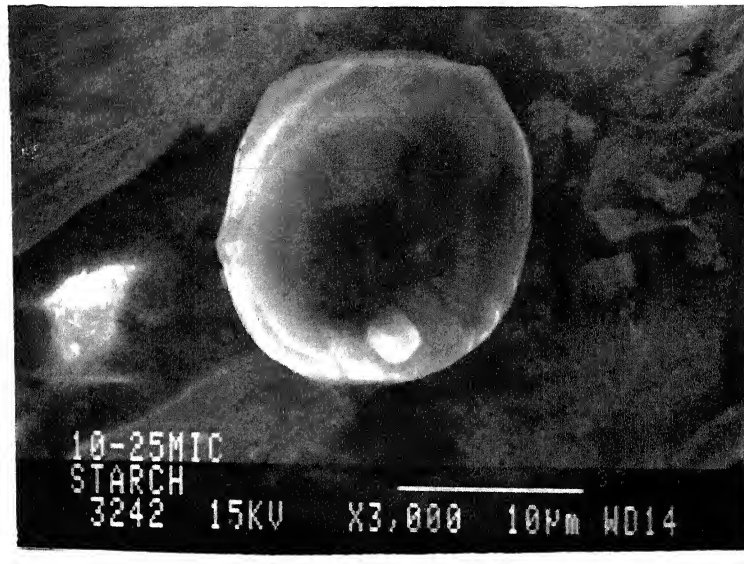


PHOTO 4.3

Starch Particle (15-25 Micron)

SILICA FLUID WITH DC FIELD

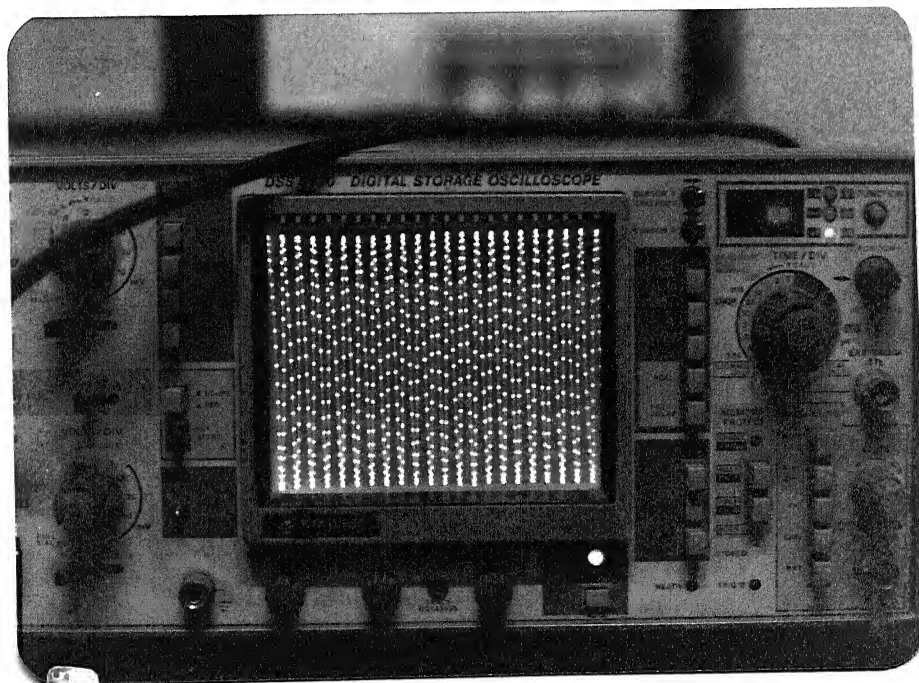


PHOTO 5.1

TR at V=0 Volts

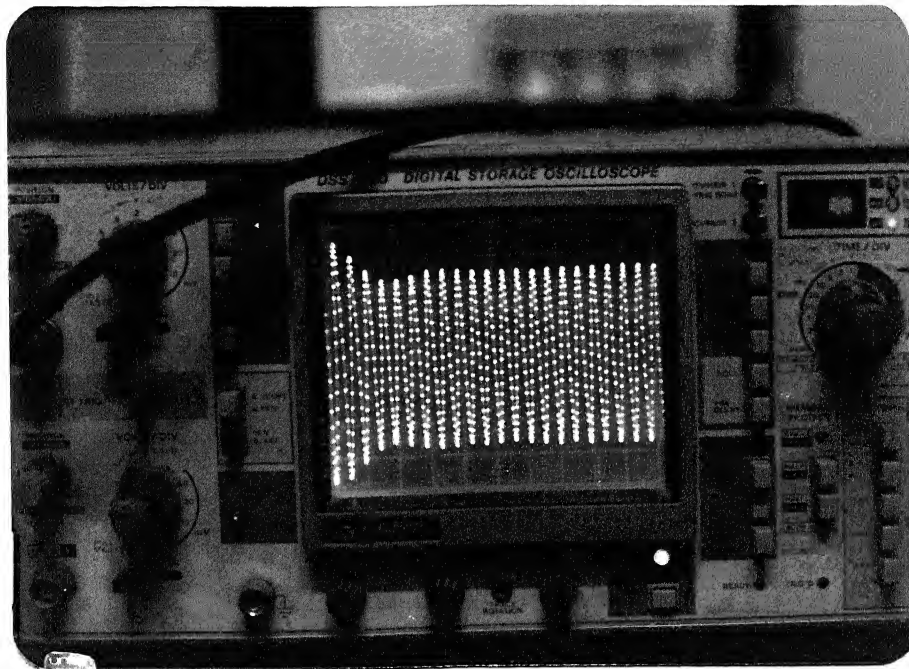


PHOTO 5.2

TR on application of DC field

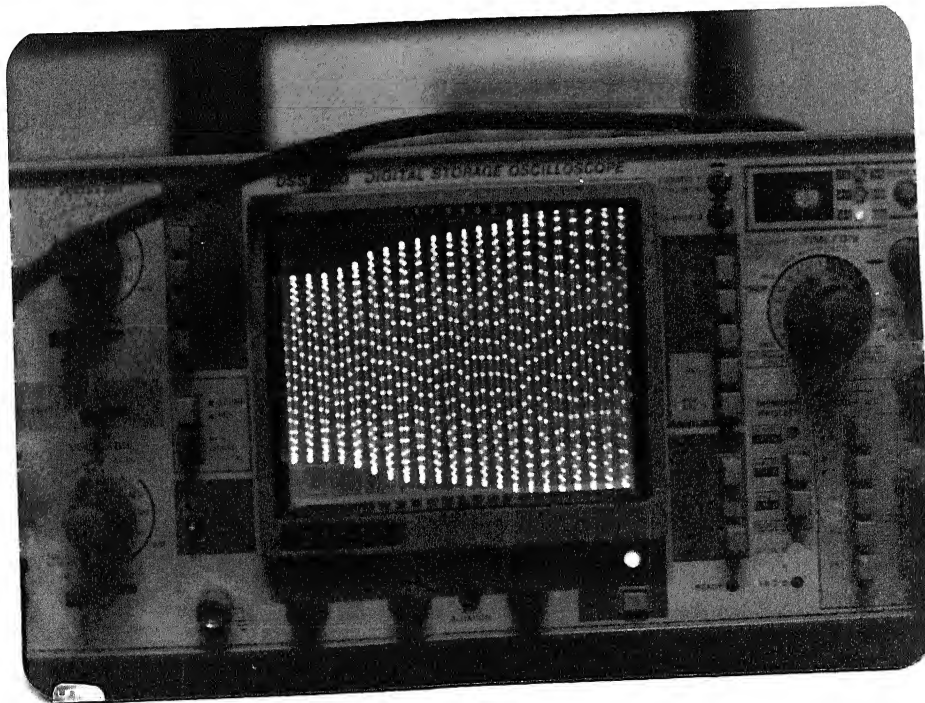


PHOTO 5.3

TR on removal of field

STARCH FLUID WITH AC FIELDS

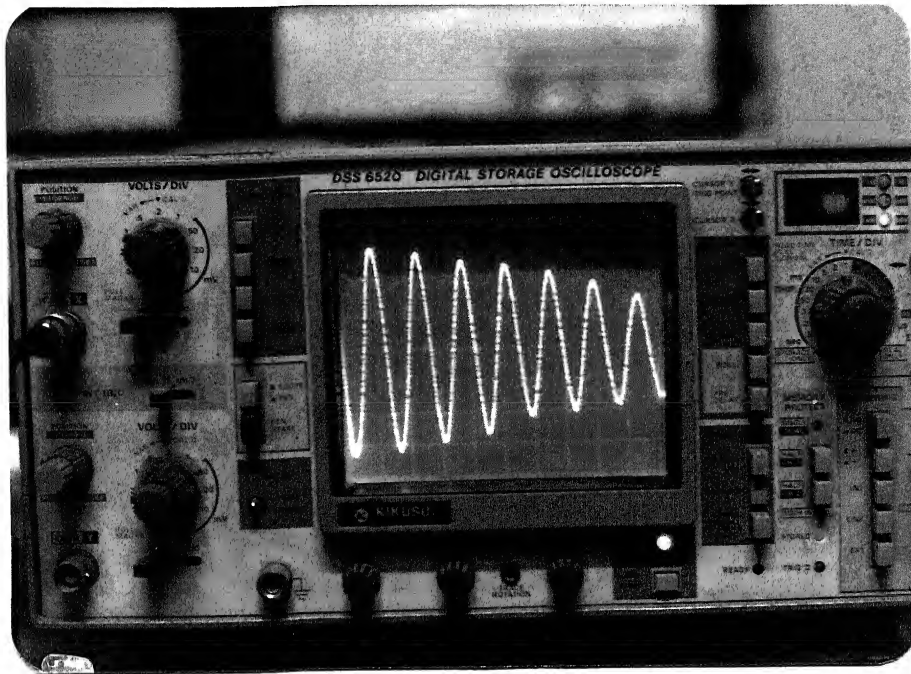


PHOTO 5.4

TR on application of AC field

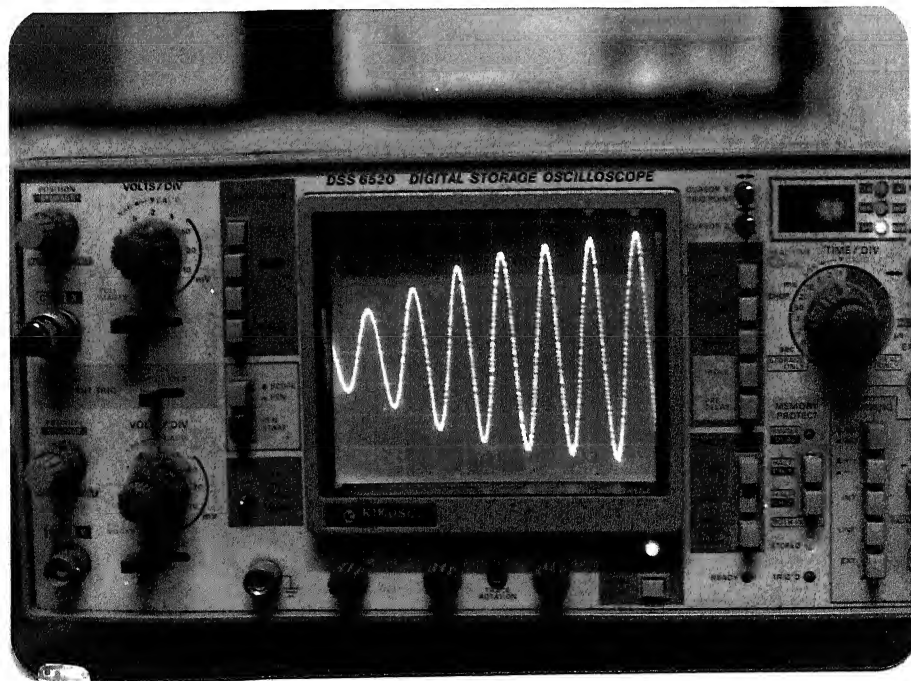


PHOTO 5.5

TR on removal of AC field

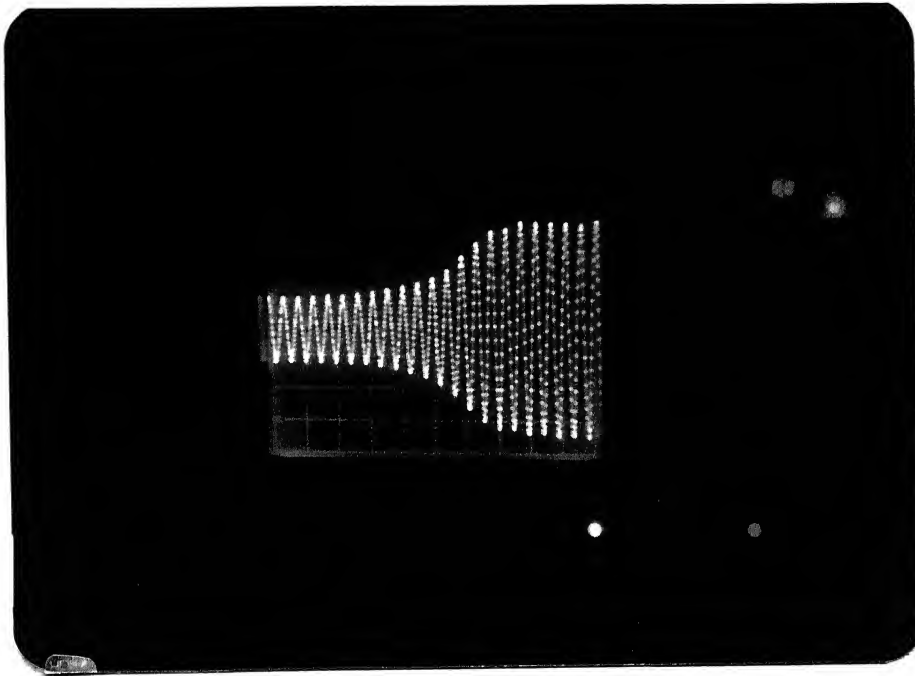


PHOTO 5.6

TR on sudden removal of AC field

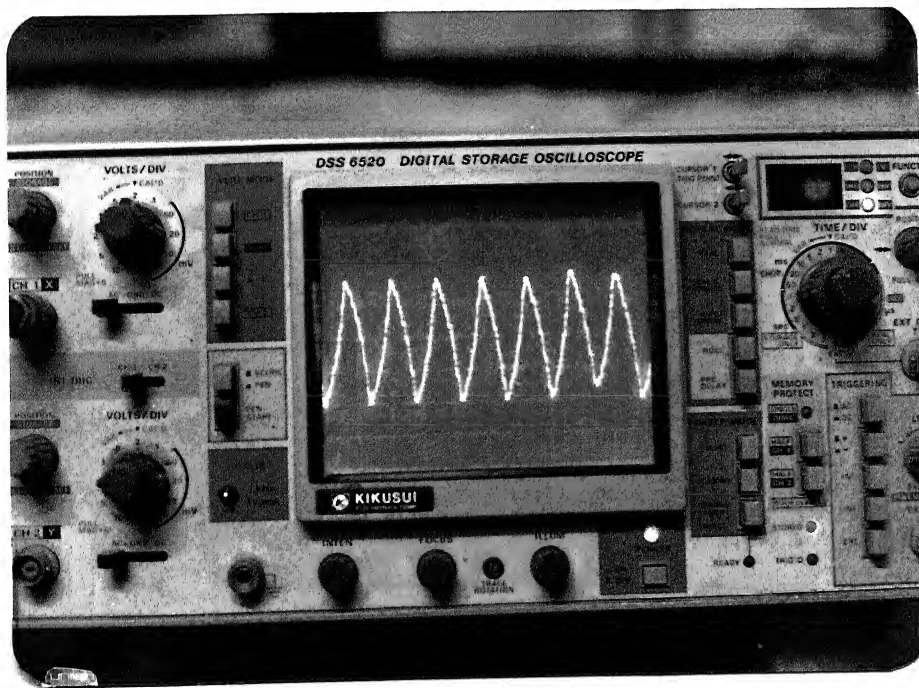


PHOTO 5.7

Velocity Profile showing non-linearity at Critical Damping at $V = 1900$ volts